AD-A133 542

(13)

ornl

ORNL-5958

OAK RIDGE NATIONAL LABORATORY

UNION CARBIDE

A Preliminary Study of Reducing the Cost of Blast Shelter for Critical Workers

C. V. Chester
D. W. Holladay

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A09 Microfiche A01

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ORNL/TM-5958	2. GOVT ACCESSION NO. AD-A133542	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A PRELIMINARY STUDY OF REDUCING THE COST OF BLAST SHELTER FOR CRITICAL WORKERS		5. TYPE OF REPORT & PERIOD COVERED FINAL REPORT
		6. PERFORMING ORG. REPORT NUMBER ORNL/TM-5958
7. AUTHOR(s) C. V. CHESTER, D. W. HOLLADAY		8. CONTRACT OR GRANT NUMBER(s) FEMA EMW E 0739
9. PERFORMING ORGANIZATION NAME AND ADDRESS OAK RIDGE NATIONAL LABORATORY POB X OAK RIDGE, TN 37830		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS FEMA WORK UNIT 1611A
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE AUG 1983
		13. NUMBER OF PAGES 154 + xix
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

SAME AS 16.

18. SUPPLEMENTARY NOTES

N/A

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

BLAST SHELTER	CIVIL DEFENSE
KEY WORKERS	CORRUGATED METAL SHELTERS
SHELTER COSTS	EARTH ARCHING

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The overall purpose of this study was to examine ways to reduce the cost of shelter for critical workers. Shelters for this purpose would be expected to have from 10 to 100 spaces and overpressure protection from 340-1360 kPa (50-200 psi).

The civil defense literature on cost was reviewed, and the cost estimates of the best designs were corrected to 1982 dollars. For shelters of the size and (contd)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(contd) p.20

hardness of interest, costs generally run higher than $1000/space. Costs usually decrease significantly with increasing shelter size, and increase with hardness. None of the concrete shelter designs reviewed have taken advantage of earth-arching. Experiments with shelters in blast tests suggest that, for granular soil, corrugated metal culvert may be the most economical shelter material.

Basement shelter space in new buildings can be constructed at low cost; however, the threat to survival of its occupants from fire in the buildings or rubble from the building's destruction cannot be managed by entrances and ventilation intakes close to the building. Escape tunnels and ventilation intakes extending out some distance from the building are required.

A design and a cost estimate of a corrugated metal shelter exploiting earth-arching for 1360 kPa (200 psi) was carried through the concept stage. It is believed the configuration used will enable the occupants to survive both the ground motion and the initial nuclear radiation from megaton weapons at this overpressure. It appears that this shelter can be constructed for somewhat under $500/space, including habitability equipment, when purchased in relatively small numbers.

A design concept for a very lightweight, high-overpressure door was developed. This door, using the membrane principle, offers the promise of being the lowest cost entranceway when in mass production.

ORNL-5958
Dist. Category UC-41

Energy Division

A PRELIMINARY STUDY OF REDUCING THE COST OF BLAST SHELTER FOR CRITICAL WORKERS

C. V. Chester
D. W. Holladay

Date Published - October 1983

For
Federal Emergency Management Agency
Washington, DC 20472
Interagency Agreements DOE 40-1197-81
and FEMA EMW-E-0739
Work Unit 1611A

Prepared by the
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. DEPARTMENT OF ENERGY
Under Contract No. W-7405-eng-26

TABLE OF CONTENTS

TABLE OF CONTENTS
(continued)

TABLE OF CONTENTS
(Continued)

EXECUTIVE SUMMARY

The overall purpose of this study was to examine ways to reduce the cost of shelter for critical workers. Shelters for this purpose would be expected to have from 10 to 100 spaces and overpressure protection from 340-1360 kPa (50-200 psi).

The civil defense literature on cost was reviewed, and the cost estimates of the best designs were corrected to 1982 dollars. For shelters of the size and hardness of interest, costs generally run higher than $1000/space. Costs/space usually decrease significantly with increasing shelter size, and increase with hardness. None of the concrete shelter designs reviewed have taken advantage of earth-arching. Experiments by the Donn Metal Products Company with a corrugated culvert shelter in the Miser's Bluff test suggest that for granular soils, corrugated metal culvert may be the most economical shelter design.

Basement shelter space in new buildings can be constructed at low cost; however, the threat to survival of its occupants from fire in the buildings or rubble from the building's destruction cannot be managed by entrances and ventilation intakes close to the building. Escape tunnels and ventilation intakes extending out some distance from the building are required.

Most of the cost of shelter is in the structure of the shelter itself. Possibly, the most effective method of reducing this cost is to exploit the phenomenon of earth-arching. The power of earth-arching has been demonstrated dramatically by experience with corrugated metal shelter in the nuclear weapons tests in the 1950s. Consistent with the simple theory of earth-arching, shelter survival depended much more heavily on the depth of cover of the shelter as a function of its span and the angle of internal friction of the soil, than on the strength of the shelter. Ten-gauge (3.57 mm thickness) corrugated metal shelters,

2.13-M (7 ft) in diameter, survived 1.689 mPa (245 psi) with 3.05-M (10 ft) of earth cover in reasonably good soil. A 7.62-M (25 ft)-diameter, arched shelter with 1.52-M (5 ft) of gravel cover survived 689 kPa (100 psi).

Experiments with shallow-buried, rectangular concrete structures at the Waterways Experiment Station demonstrated substantial strength enhancement with depths of cover as little as 1/5 of the span, using sand. Very little deflection of the roof was required to transfer most of the load on it to the walls and the surrounding sand.

A conceptual design and a cost estimate of a corrugated metal shelter was carried through the concept stage for 1.35 MPa (200 psi). It is believed the configuration used will enable the occupants to survive both the ground motion and the initial nuclear radiation from megaton weapons at this overpressure. The design was developed in consultation with the local vendor of Republic Steel Corrugated Culvert. Using their prices, it appears that this shelter can be constructed for somewhat under $500/space, including habitability equipment, when purchased in relatively small numbers.

A design concept for a very lightweight, high-overpressure door was developed. This door, using the membrane principle, offers the promise of being the lowest cost entranceway when in mass production.

ACKNOWLEDGMENT

The authors wish to acknowledge the courtesy and cooperation of Earl May of Knoxville Metal Culvert Company and Dan Cannon of the Drainage Products Division of Republic Steel who provided fabrication and cost information on metal culvert for shelters. Mr. Ed York of the Boeing Corporation and Cresson Kearny offered many helpful observations and suggestions. Reviews of the report and many constructive comments were provided by Don Bettge and Ralph Swisher of FEMA. The authors would never have stayed on schedule without the efforts (beyond the call of duty) of Ruby Thurmer in editing and Judy Coleman and Nancy Watlington in word processing and assembling the report.

CONVERSION FACTORS FOR SI UNITS

English units have been retained in the body of this report. The report is directed principally to the construction industry, and refers to commercially available materials and sizes commonly expressed in English units. The report quotes extensively from earlier work expressed entirely in English units. Conversion factors for SI units are given below:

To Convert From:	To:	Multiply By:
Foot (ft)	Meter (m)	0.3048
Square Foot (ft^2)	Square Meter (m^2)	0.0929
Cubic Feet (ft^3)	Cubic Meter (m^3)	0.0283
Inch (in.)	Meter (m)	0.0254
Mile (mi)	Meter (m)	1.609
Square Foot (ft^2)	Meter (m)	.0929
Pound-Force/in^2 (psi)	Kilopascal (kPa)	6.894
Atmosphere (14.7 psi)	Kilopascal (kPa)	101.4
Gravity (32.2 ft/sec^2)	$Meter/sec^2$	9.8

PRELIMINARY STUDY OF REDUCING THE COST OF BLAST SHELTER FOR CRITICAL WORKERS

ABSTRACT

The overall purpose of this study was to examine ways to reduce the cost of shelter for critical workers. Shelters for this purpose would be expected to have from 10 to 100 spaces and overpressure protection from 340-1360 kPa (50-200 psi).

The civil defense literature on cost was reviewed, and the cost estimates of the best designs were corrected to 1982 dollars. For shelters of the size and hardness of interest, costs generally run higher than $1000/space. Costs usually decrease significantly with increasing shelter size, and increase with hardness. None of the concrete shelter designs reviewed have taken advantage of earth-arching. Experiments with shelters in blast tests suggest that, for granular soil, corrugated metal culvert may be the most economical shelter material.

Basement shelter space in new buildings can be constructed at low cost; however, the threat to survival of its occupants from fire in the buildings or rubble from the building's destruction cannot be managed by entrances and ventilation intakes close to the building. Escape tunnels and ventilation intakes extending out some distance from the building are required.

A design and a cost estimate of a corrugated metal shelter exploiting earth-arching for 1360 kPa (200 psi) was carried through the concept stage. It is believed the configuration used will enable the occupants to survive both the ground motion and the initial nuclear radiation from megaton weapons at this overpressure. It appears that this shelter can be constructed for somewhat under $500/space, including habitability equipment, when purchased in relatively small numbers.

A design concept for a very lightweight, high-overpressure door was developed. This door, using the membrane principle, offers the promise of being the lowest cost entranceway when in mass production.

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LITERATURE REVIEW OF CRITICAL FACTORS THAT AFFECT THE COST OF BLAST SHELTERS AND METHODS OF REDUCING THE COST

C. V. Chester
D. W. Holladay*

1. INTRODUCTION

This report covers two main topics. In the first portion there is a literature review focused on identifying the various cost factors involved in blast shelter design and the reasons, where possible, for the wide range of values reported for the critical cost figure -- dollars/ shelter space. Secondly, there is a discussion of construction techniques, structural concepts, and facets of construction procedures, in general, that can be utilized to reduce the cost of shelters.

There are essentially five major parameters, each with its own subset of variables, causing wide variations in cost that have been reported by various designers of blast shelters throughout the past 20-odd years. These parameters may be briefly summarized as follows:

(1) There is a wide variation in the specific cost factors included in each report - the list of cost factors is rather extensive and will be presented in detail in the text. The factors traditionally considered in blast shelter design may be divided into three main categories:

(a) The basic protective structure which includes the main shelter structure, ventilation shafts, blast closure valves, shelter entranceway, exit, emergency exit, and associated earthwork;

(b) The equipment for habitation such as ventilation and air conditioning, electrical, hotel accommodations, sanitation, food, and water; and

(c) Non-hardware considerations such as engineer and architectural fees, contractor overhead, profits, and contingencies, land costs, bonds, taxes, and insurance, etc.

---

*Chemical Technology Division.

(2) Many different types of architectural design have been proposed for blast shelter construction. Specifically, the list should include such configurations as horizontal rectangular, horizontal cylinder, vertical cylinder (silo), spherical, and semicircular arch. Each type of structure may be designed with multiple floors, various interior arrangements, and with different materials of construction, such as timber, concrete, smooth steel, corrugated steel, or fiberglass.

(3) There are wide ranges of blast overpressure and shelter occupancy which may be considered in design. As is well-known to students of blast shelter design, there are major variations in shelter costs associated with different overpressure or number of spaces. No effort to devise a correlation for shelter cost as a function of occupancy, pressure, and architectural design has been very successful. The latter parameter includes so many factors that it may effectively render such a correlation improbable at best. Krupka (1964) attempted to express shelter costs as a function of overpressure <u>only</u> with an equation of the form

$$\text{Cost} = A + Bp^{c},$$

where A and B are constants, p is overpressure (psi), and c is a constant. The constant A was adjusted to account for habitability items such as mechanical-electrical, sanitation, food, water, etc. Such a relation is useful for general discussion but has not been considered widely applicable for predicting cost as a function of hardness. (See also Haaland, 1970). Perhaps it would be constructive to attempt to devise better correlations for costs as a function of overpressure, space, etc., but this effort presently is not included here.

(4) Different design factors can be considered in the design of the basic shell structure and entranceways:

(a) Values assumed for ductility factor, ratio of maximum deflection to deflection-at-yield,

(b) Assumptions about soil-structure interaction,

(c) Length of spans,

(d) Strength of concrete,

(e) Extent of reinforcement,

(f) Better understanding of the type of interior layout which is dictated by behavior of the inhabitants.

(5) Finally, a simple factor, but nonetheless an important one, is the effect of inflation on prices. More or less similar designs presented over a period of years will naturally vary in price because of inflation so that for shelter comparisons all costs should be normalized to the same year.

A final comment for any cost factor comparison is that in general no two estimators will arrive at the same cost figure for the same job.

This report is organized such that several of the major blast shelter studies are briefly reviewed with focus on the purpose of the study, type of cost factors included with assumptions, types of construction details, and major conclusions.

For each review, the following information on the major parameters affecting costs, as noted previously, is presented:

(a) The cost factors included in the design of specific shelters are listed.

(b) The types of architectural design and materials of construction are enumerated and compared on the basis of cost.

(c) The effects of occupancy and overpressure on costs where appropriate are compared, mainly in tables included in the appendices.

(d) The inclusion of a discussion about assumptions and theories of strengths of material used in each study is a complex task and an in-depth discussion of these factors is beyond the scope of this review. However, where possible, for some of the reports the assumptions about concrete strength, span length, and methods of construction will be indicated. Unfortunately, in most of the reports, there is no in-depth analysis of these factors. If all other cost factors are equal in different design studies (a rare occurrence), differences in shelter cost can often be traced to different assumptions on design and differing cost estimates for in-place structural members.

For the sake of organization much of the information on the costs is presented in tabular form in the Appendices.

In general, the costs for all of the shelters in a single study were plotted as a function (at constant occupancy) of overpressure so that the most economical shelters could be identified. Final graphs and arguments are presented in the discussion and summary section for costs (updated to 1982) of the most competitive blast shelter designs.

Finally, the primary focus of this study was on shelters ranging from family size to 100-500 occupants (suitable for critical industrial workers). Because of the cost, large civil defense programs for protecting in excess of 1-5 million people from blast conditions are not probable in the immediate future. Relocation is the most economical method of protecting most of the population. We will not enter into a discussion here of the feasibility and costs of constructing large shelters for people in fallout areas. In some studies which are reviewed, there will be limited discussion of single shelters housing in excess of 500 persons, as for shelter programs for housing entire cities, but these shelters are de-emphasized in relation to those housing 5-500 occupants.

Although some shelter designs for overpressures as high as 1500 psi are included, the primary focus of this review was to emphasize design and costs of blast shelters for overpressures in the range of 50-200 psi. This range was selected because it is of interest for shelters for critical workers and does not require very expensive shock isolation systems.

In the second portion of this report, some innovative construction methods and optional shelter uses for achieving cost reduction are presented. Among the construction concepts which are discussed are the membrane door used to protect a vertical entrance, (with the aid of a concrete collar), and a sand-protected door. The dual-use concept is based on the notion that facilities which function for normal use in peacetime, which pays most of the cost, can be upgraded in times of crisis to a capability for withstanding significant blast overpressure and associated radiation. Methods of crisis upgrading discussed include moveable support columns, portable shielding concrete blocks, sand closure for orifices, and crisis burial. Consideration is also given to general cost-saving construction concepts such as mass production and the learning curve. A discussion is included of two specific types of shelters which are examples of the types of arguments we are presenting, i.e., single purpose shelter design and dual-use shelter. The discussion of these two structures includes plan drawings, modes of use and application, outfitting, and cost estimates. These shelters are:

(a) Corrugated steel culvert, which is a structure particularly suited for application of ingenious construction techniques and serendipitous structural-soil interactions, and

(b) A wine cellar constructed of concrete which can function as a shelter in times of crisis.

Finally, it is obvious that even the very best designs are only plans whose ultimate worth can be proven only by actual construction and testing. Suggestions are offered on the best routes for future work to assess the functionality of the various proposed cost-saving concepts and shelter designs.

2. LITERATURE REVIEW

2.1 LARGE SHELTERS

At the beginning of this study, it should be emphasized that there is no claim that all design studies of blast shelters for the past 20-25 years are included in this review. However, it is intended that those included here are representative of the whole sample. An effort has been made to include many of the most often-quoted studies in this review (Table 2.1). Goen, et al. (1966) prepared a rather extensive review of major blast shelter studies available at that time (1966). Included in their assessments were the IITRI studies [Havers (1963), Havers and Lukes (1965), Stevenson and Havers (1965)] and other often-cited reports [Forrestal (1963), Holmes and Narver (1969), Krupka (1963)]. It is not the intent of this review to try to extend Goen's parametric analysis to all blast shelter studies. However, as stated in the introduction, the many reasons for cost variation will be identified and costs for a reasonable set of cost factors will be updated to estimated 1982 dollars. The reviews will be discussed in roughly chronological order.

2.1.1 Lawrence Livermore, UCRL 6654, A Study of Design and Cost Data for Family and Small-Group Fallout Shelters, October, 1961

The purpose of this study (LLL, 1961) was to develop designs and cost data for five durable family and small-group fallout shelters. Both austere and commodious designs were considered. For the austere case, water was provided on the basis of 1/2 gal./day and food consisted of iron rations. Sanitary facilities were a chemical toilet and an additional waste can, while sleeping accomodations were 6 air mattresses and homemade bunks. Lighting was provided by lantern and flashlights. Estimated cost of the habitability package for six people was $216 in 1961, and $530 in 1982. For the commodious case, water was provided on the basis of 1 gal./day, while food consisted of canned goods. Sanitation was the same as for the austere case and sleeping quarters were built-in bunks and mattresses. Lighting was provided by means of electrical

Table 2.1 Design and Construction Faccors Considered in Major Blast Shelter Studies

Design Study	Site Preparation	Excavation	Backfill	Structural	Shock Isolation	Entranceways	Mechanical	Electrical	Furnishings	Food & Water	Land Costs	Contractor OP&C	Govt. Supervision	Communications & Monitoring	Architect/Engineer	Bonds & Insurance
Lawrence Livermore	ns	x	x	x	o	ns	x	x	x	x	o	x	o	x	o	o
GATC '63	x	x	x	x	o	x	o	x	o	o	o	o	o	o	o	o
A&W '63	ns	x	x	x	x	o	o	o	o	o	o	x	o	o	o	o
Havers '63	o	x	x	x	o	x	o	o	o	o	o	x	o	o	o	o
Havers & Lukes '65	o	x	x	x	o	o	o	o	o	o	o	x	o	o	o	o
Stevenson & Havers '65	o	x	x	x	o	x	o	o	o	o	o	x	o	o	o	o
U. of Arizona '64	ns	x	x	x	o	x	x	x	x	x	o	o	o	o	o	o
Krupka '64	ns	ns	ns	x	o	x	x	x	x	x	o	o	o	o	o	o
Curione (SRI)'67	ns	x	x	x	o	x	x	x	o	o	o	x	o	o	o	o
Bechtel '67	x	x	x	x	o	x	x	x	x	o	o	x	o	o	x	o
L&S '68																
Option 1	x	x	x	x	o	x	o	o	o	o	o	x	o	o	o	o
Option 2	x	x	x	x	o	x	x	x	o	o	o	x	o	o	o	o
Option 3	x	x	x	x	o	x	x	x	o	o	o	x	o	o	o	o
Option 4	x	x	x	x	o	x	o	o	o	o	o	x	o	o	o	o
Option 5	x	x	x	x	o	x	x	x	o	o	o	x	o	o	o	o
Option 6	x	x	x	x	o	x	x	x	o	o	o	x	o	o	o	o

Table 2.1 (Cont'd). Design and Construction Factors Considered in Major Blast Shelter Studies

Design Study	Site Preparation	Excavation	Backfill	Structural	Shock Isolation	Entranceways	Mechanical	Electrical	Furnishings	Food & Water	Land Costs	Contractor OP&C	Govt. Supervision	Communications & Monitoring	Architect/Engineer	Bonds & Insurance
Holmes & Narver '69	ns	x	x	x	o	o	o	o	o	o	o	o	o	o	o	o
Kamath & Wright '80	x	x	x	x	o	x	x	x	o	o	o	x	o	o	o	o

NOTE: x = included
o = excluded
ns = not specified

outlets backed up with an emergency generator. This commodious package was estimated for 6 people to be $385 in 1961, $944 in 1982.

The cost factors included in this study were among the most extensive of any study in this review (see enumerated in Table 2.2 and in master Table 2.1). Table 2.2 shows the approximate costs of the various factors for the 5 different designs for both austere and commodious cases adjusted to 1982 dollars. Of course the utility of these designs is very limited because they are not extended to either multiple cases of design overpressure or occupancy. Of interest is that the commodious case, for the same occupancy, appears to cost about 2.5 times as much as for the austere case. In general, for four of the shelters at family size the cost/occupant (at 12 ft^2/ person) is in the range of $700-800 (1982) for the austere case and $1100 to $2100 for the commodious case. Because of some variations in sizes of the designs for the commodious case, the choice of the optimum design is difficult, but it appears that either the reinforced concrete or concrete block design would be acceptable. It is well to stress that in shelter design-cost analyses, structure cross section and interiors have subtle but important bearing on habitability. In the appendix of the UCRL report, fairly extensive cost figures for itemized combinations are given. These include lists of:

(1) Materials for construction (quantities and cost per unit),

(2) Labor costs,

(3) Contractor's overhead profit and contingencies (25%),

(4) Plumbing equipment,

(5) Electrical wiring and items,

(6) Ventilation equipment.

Table 2.2 Summary of Shelter Costs for Lawrence Livermore Fallout Shelter, 1982 Dollars

Cost Components	Kind of Shelter									
	Reinforced Concrete		Concrete Block		Concrete Panel		Multiple Pipe		Concrete Pipe	
	Aust. (3-6 persons)	Commod.	Aust. (5-8 persons)	Commod.	Aust. (4-6	Commod. 8-14p.)	Aust. (5-8 persons)	Commod.	Aust. (2-4	Commod. 5-8p.)
Basic Shelter	3585	9231	5130	11,148	4917	8403	5639	9199	4875	7417
Installation	0	1032	0	1,380	926	3194	0	1602	1458	4500
Ventilation	348	540	348	540	348	884	348	540	348	540
Hotel Accomodations	530	944	530	944	530	1471	530	944	530	944
Control Package	120	120	120	120	120	120	120	120	120	120
Power Package	0	800	0	800	0	800	0	800	0	800
TOTAL COST	4581	12,667	6128	14,932	6841	14,872	6637	13,205	7331	14,381
Approximate Cost/Occupant (12 ft^2/person)	761	2101	757	1,874	1133	1085	825	1644	1833	1784

Cost factors for updating prices to 1982:

Construction - Engineering News Index
Ventilation - Statistical Abstracts, 1981; Factor = 225/99
Hotel Accomodations - Statistical Abstracts; Factor = 230/93.8
Control Package - Factor = 2.6
Power Package - Statistical Abstract; Factor = 225/99.5

Detailed construction drawings were not given, but extensive plan drawings of the various designs are presented. This study by Lawrence Livermore was included to serve as a sort of base cost case for structures designed to withstand only minimal pressures.

2.1.2 M.J. Forrestal, GATC Study, Protection Against High Blast Overpressure and Ground Shock, Feb., 1963

The purpose of this study (Forrestal, 1963) was to develop concepts to serve as a partial guide to the evaluation, design, and construction of civil defense shelters useful in the region of high blast overpressures, with the range considered in design varying from 100 to 1500 psi. Several structural configurations (horizontal cylinder, vertical silo, sphere) were considered with varying floor and interior arrangements to allow for occupancy of either 100 or 300 spaces.

Because of the unusually harsh conditions presented by the high blast pressures considered in this study, it was necessary to consider all nuclear weapons effects. Factors considered were shielding against initial nuclear radiation, ground motion, and resultant effects on shelter occupants; however, no costs for shock isolation were included in the economic analyses. "Shock spectra" which give predicted ground shock motion for overpressures of 100, 500, 1000 and 1500 psi were included. Assuming low seismic-velocity soil, these spectra plot maximum absolute acceleration and relative displacement between the mass of a simple, single-degree-of-freedom, mass-spring system and the support for the spring as a function of the natural frequency of the system. Shock isolation is critical above 100 psi in most soils, due to large displacements.

The cost factors considered in the GATC study were quite limited, including only such direct costs as basic earthwork, main shell structure with ends and interior structure, and entrances/exits. Thus, there was no consideration of major non-structural cost items such as mechanical and ventilation equipment, electrical needs, hotel accommodations, control package, etc. (See Table 2.1). In general, the basic shelter

installation contributes about 50-60% of the total costs, with the remainder being contributed by indirect habitability items.

The costs for the several designs given by Forrestal were adjusted to 1982 prices for several cases - shock isolation protection level 1, protection level 3, and no shock isolation (See Table A-1, Appendix A). Shock isolation estimates were taken from Amman and Whitney. Since A & W estimated shock isolation costs for spaces of only 100 and 200, values were estimated from that data for spaces of 500 and 1000. Although it was probably too conservative, costs for shock protection at 1000 and 1500 psi were estimated to be about the same as those for 500 psi. Mechanical and electrical equipment were estimated to be 25% of the basic shelter costs (including entrances). No estimate was made for site preparation. Prices for the shelter, including main structure, entranceway, mechanical and electrical, and shock isolation were adjusted to 1982 prices, then 20% was added for contractor's overhead, profit, and contingencies.

Among the designs considered in the GATC study, the least expensive appears to be the 3-story, horizontal steel cylinder with 500 spaces (Table A-1). However, at a fixed pressure of 500 psi, the most economical structures are the 2-story (18-ft) and 3-story (28-ft), horizontal concrete cylinders.

No detailed construction drawings were presented. The available drawings are relatively simple plan views giving basic structure, but no details are given for bunks, sanitation, storage space, etc. Costs for individual shelters are not itemized, but a price list for basic structural costs and labor is included and contains such items as: hand and machine excavation and backfill costs/yd^3, concrete costs/yd^3, form prices/ft^2, and cost of steel shells.

2.1.3 Ammann and Whitney, Study of Shock Isolation Methods for Civil Defense Shelters, November, 1963

The basic purpose of this study (Ammann and Whitney, 1960 and 1963) was to develop specific shock isolation systems to provide protection for personnel when they were housed in shallow-buried blast shelters designed for various combinations of occupancy (10, 100, 250 spaces) and blast overpressure (25, 100, and 300 psi). Cost figures were developed

for the various design conditions, including shock isolation techniques. Based on an extensive literature review and a separate design effort, shock environment and shock tolerance criteria were developed.

In general, more severe groundshock effects are produced by surface bursts than by airbursts. For design purposes, ground motions produced by nuclear surface bursts are considered to be induced by two different factors, air-induced shock and direct-transmitted groundshock. Because the direct-induced groundshock is a transmission of energy into the ground in the immediate vicinity of the burst, it is normally of major importance only in very high-pressure regions. The A & W study focused primarily on air-induced effects because they were the major factors for the peak overpressures and design conditions considered.

The shock-front velocity of the air-blast wave and the peak incident pressure decrease as the distance from ground zero increases. Assuming a near-constant seismic velocity, a point is reached away from ground zero beyond which ground motions will arrive prior to the air-blast. Initial upward motions may be produced by this ground motion, but these early disturbances are generally of minor magnitude relative to the motions induced by the main air-blast wave. For typical soil sites, the ground motions will precede the air-blast wave in ground ranges where the peak incident overpressures are less than about 100 psi.

Unless the blast structure is extremely long parallel to the direction of the blast wave, the wave will completely engulf the structure. If the loading lasts for several seconds (as with megaton yields), the structure will experience a peak displacement of about the same order of magnitude as that of the peak free field displacement because of the similarity of the impulse felt by the structure to that of the free field impulse. However, the peak acceleration in the structure would be less than the peak ground acceleration in the free field due to the longer rise time of the structure in loading.

The phenomena associated with the interaction of the structure and surrounding soil are very complex to analyze. It is necessary to resort to simplified conditions to obtain approximate solutions. For

design purposes a solution can be obtained by using ground shock response spectra where the shock effects of estimated peak ground motions are represented in terms of the shock environment.

The following accelerations were considered by A&W for personnel restrained in chairs or cots: 2g for less than 10 c.p.s.; 5g for 10-20 c.p.s.; 7g for 20-40 c.p.s; and 10 g above 40 c.p.s. These values were considered safe for personnel subjected to the vibration in a shock-isolated support caused by groundshock motions. The 2g value was adopted for their study because of the elaborate restraining devices required for the higher accelerations and because old people and children would probably be in the shelters. For the horizontal and vertical, 0.50g and 0.75g were adopted for non-restrained personnel either standing, sitting, or reclining. Extensive design spectra are given in this study relating maximum velocity, frequency, acceleration, and overpressure.

Three levels of protection for personnel from blast-induced shocks are presented by A & W. The first level is the most elaborate and costly because it requires a shock-isolated interior platform to reduce the high accelerations of the structure to values which are non-injurious to the personnel. The second protection level is based on the application of cushioning material to the floor, walls, and other surfaces upon which personnel could impact. In this level, the floor is designed as part of the structural shell and would move with the same acceleration. The cushioning material achieves its protection by shielding personnel from: (1) impact at velocities above 10 ft/sec caused by falling; (2) impact with corners, edges, and overhead objects; and (3) compression waves transmitted through walls. In general, level 2 provides less protection than level 1. The third protection level, the least costly, is based on the use of a limited amount of protective cushioning material. Again, the design calls for the floor to be part of the shell. Use of cushioning material is limited to the following functions: (1) prevention of impact with corners, edges, and overhead objects; (2) protection from compression waves transmitted through exterior walls.

For the overpressures considered by A & W, the only impact velocities which exceed 10 ft/sec are those due to personnel off-balance. For this case, the third protection level assumes off-balance personnel will have their fall cushioned by impact with large areas of the body or arms with no protective cushioning material on the floor and walls. Because of this, the probability of injury is the greatest for protection level 3.

The cost factors included in the A & W study were limited to include only the direct costs: excavation, backfill, main structure, contractor's overhead, profit and contingency and shock isolation (see Table 2.2). Excluded were entrances/exits, ventilation, mechanical and electrical, and other habitability items. Costs were updated to 1982 for one- and two-story horizontal concrete cylinders for three cases - shock protection levels 1 and 3 and no shock isolation. Because no figures for entrance costs were presented by A & W, these costs were estimated according to IITRI data (Stevenson and Havers 1965) for blast resistant shelters. Although entrance costs expressed as cost/space generally range from 25 to 40% of the base cost according to Stevenson and Havers, the entrance values used here are less than that (10 to 15%) because the cost/space numbers of A & W were considerably higher than those of the IITRI studies. Mechanical and electrical equipment were estimated as 25% of the basic shelter cost/structure, earth-work, entrance. Cost/space values for shock isolation were as given by A & W. Costs were adjusted to 1982 according to the Engineering News Record Index. The costs for one-story concrete cylinders designed by A & W are higher than those for comparable one-story concrete cylinders of the IITRI studies at the same occupancy and pressure, primarily because of the initial differences in basic shell structure estimates.

Among the structures considered in the A & W study, the least expensive is the two-story, horizontal, concrete cylinder while the most expensive appears to be the concrete arch (Table A-2). Like the GATC studies, there is considerable cost variation with pressure, shelter spaces, and type of design (see Table A-2).

2.1.4 IITRI Studies - J. A. Havers, Structural Materials for Hardened Personnel Shelters, Dec., 1963; J. A. Havers and J. J. Lukes, Structural Cost Studies for Hardened Shelters, Jan., 1965; J. D. Stevenson and J. A. Havers, Entranceways and Exits for Blast-Resistant Fully-Buried Personnel Shelters, Sept., 1965.

These reports (Havers, 1963; Havers and Lukes, 1965; Stevenson and Havers, 1965) must certainly be considered among the most detailed of all the U.S. studies of blast shelter ever conducted. The objective of the initial Havers study was to evaluate availability and in-place costs for certain structural materials which could be utilized in a large-scale effort to construct a significant blast shelter program in the U.S.

The estimated shelter costs were derived for only structural portions of buried blast shelters. Thus, the in-place costs included all necessary material, equipment, and labor, which is normally supplied by a general contractor. The cost included basic structural material, fabrication, transportation, and erection. An additional 40% was allowed for job overhead, profit, and contingencies. Not included in the costs were allowances for architect-engineer services, site acquisition and preparation, or charges for various government agencies which might be associated with implementation and performance of the construction. Also, there was no provision for such items as blast closures and fittings, mechanical ventilation and electrical equipment, or communications and monitoring devices.

The costs of these items, which comprise a significant portion of the total cost, are usually strongly influenced by shelter interior layout and shell design. Thus, there is a need for estimation of total shelter costs with some consideration of the IITRI techniques.

With the cost and design relationships developed by Havers as the basis, the in-place structural costs of 500- and 1000-space, fully-buried shelters were derived as functions of their critical parameters: loading level, shelter design, structural material, and structural system. By optimization of these designs, minimum structural-cost

relationships were developed for shelter capacities of 500 and 1000 spaces as functions of overpressure in the range of 10 to 200 psi. (Havers & Lukes, 1965).

The basic cost factors considered in the IITRI studies are summarized in Table 2.1. The initial cost/space estimated in these studies for the several types of shelter configuration are argumentatively among the lowest of any blast shelter study (see Tables A-3, A-4, A-5). The low values can probably be attributed to the following: (1) the cost factors included in the cost analyses were limited; (2) cost minimization arguments were extensively applied; and (3) certain types of design techniques not normally considered by other designers were included.

Goen, et al. (1966) presented generalized parametric cost analyses of concrete cubicles and concrete arches (their Chapter III), with the validity of the analyses based on the IITRI design methods and studies. Apparently, these structures were selected because for many studies they had been shown to be the most economical.

The original IITRI estimates of costs/space for the various shelter designs, overpressures, and number of spaces are included in Tables A-3, A-4, and A-5. These cost figures were adjusted for comparison to other blast shelter studies in the following manner:

(1) The base price was obtained by subtracting the 40% overhead, profit, and contingency (O,P,C).

(2) For the Havers and Lukes study,(1965) it was necessary to estimate costs of entrances developed by Stevenson and Havers (1965) in the third IITRI study. Costs for entrances were already included in the costs for the Havers study (1963).

(3) Twenty-five percent (25%) of the base structure cost (structure, earthwork, entrance) was added back to the estimate for mechanical and electrical equipment.

(4) Three levels of shock isolation were considered following the arguments of Ammann and Whitney - protection level 1, protection level 3, and no shock isolation. Estimates for shock protection at 500 and 2000 spaces were derived from A&W estimates for 100 and 250 spaces.

(5) Finally, these adjusted prices were further adjusted up to 1982 costs (with the Engineering News-Record Index) and 20% was added for contractor's overhead, profit, and contingency.

The major conclusions of the IITRI studies were: the in-place structural costs of a fully-buried blast shelter are significantly reduced as the number of spaces is increased. This relationship was true for all cases and was independent of the peak overpressure in the range considered (10-200 psi). The structural arrangement corresponding to minimum in-place structural cost was related to the peak surface overpressure and shelter design and configuration. The use of short spans for flexural members in the rectangular cubicle gave maximum economy with the lower limit for the span being determined by the interior layout.

The most economical shelters in the IITRI studies are summarized below with the pressure ranges indicating where they are most economical and including the cost/occupant estimated in 1982 dollars.

The cost figures for the IITRI studies have been improved by addition of such features as uniform entrance/mechanical and electrical equipment, shock protection options, and uniform contractor's O, P, and C. Complete data are included in Tables A-3 thru A-5. The most economical structures for their design factors at different levels of occupancy as a function of overpressure can be deduced from the tables. These economical structures are summarized in Table 2.3.

The following discussions of economical shelters according to IITRI designs are based on the cost factors previously discussed and updated to 1982 dollars. Timber structures are omitted because of long-term maintenance problems.

For Havers' designs for 100-space shelters, with no shock isolation, the most economical shelter for pressures from 10 to 150 psi was the one-story concrete cubicle, 7-ft. bay. Above 150 psi, the one-story concrete cubicle was the most economical. The concrete arch structure showed good economy for pressures up to 75-100 psi, but apparently at 100 psi, the cost for the arch began to escalate rapidly.

Table 2.3 Economical Shelters from IITRI Studies

Shelter Type	Number of Spaces	Pressure Range (psi)	Shock Isolation Level	Cost Range (1982 $)
1-story concrete cubicle, 7-ft bay	100	10-300	1	350-1750
1-story concrete arch, vertical end	100	10-100	1	416-1391
1-story concrete cylinder	100	50-300	1	610-1654
2-story concrete cylinder	100	50-300	1	658-1606
1-story concrete cubicle, 7-ft bay	100	10-300	3	350-1328
1-story concrete arch, vertical end	100	10-300	3	416-904
1-story concrete cylinder	100	50-300	3	610-1232
2-story concrete cylinder	100	50-300	3	658-1307
1-story concrete cubicle, 7-ft bay	100	10-300	None	350-934
1-story concrete arch, vertical end	100	10-100	None	416-662
1-story concrete cylinder	100	50-300	None	610-838
2-story concrete cylinder	100	50-300	None	658-912
1-story steel cubicle	500	10-25	1	236-285
1-story concrete cubicle	500	25-100	1	300-776
1-story concrete arch	500	50-100	1	342-794
1-story concrete cylinder	500	100-350	1	790-991
2-story concrete cylinder	500	100-350	1	794-960
1-story concrete cubicle	500	10-25	None	254-300
1-story steel cubicle	500	10-25	None	236-300
2-story concrete cylinder	500	100-350	None	377-522
1-story concrete cylinder	500	100-350	None	434-592
1-story steel cubicle	500	10-25	3	236-310
1-story concrete cubicle	500	25-65	3	300-475
1-story concrete arch	500	50-65	3	435-470
2-story concrete cylinder	500	65-350	3	470-690
1-story structural steel cubicle	1000	10-20	None	215-268
1-story concrete cubicle	1000	20-50	None	268-320
2-story concrete cylinder	1000	50-350	None	320-434
1-story structural steel cubicle	1000	10-20	1	215-268
1-story concrete arch	1000	50-100	1	550-667
1-story concrete cubicle	1000	50-100	1	550-630
1-story concrete cylinder	1000	100-350	1	662-808
2-story concrete cylinder	1000	100-350	1	654-785
1-story structural steel cubicle	1000	10-20	3	215-265
1-story concrete cubicle	1000	20-50	3	265-386
2-story concrete cylinder	1000	50-350	3	390-553

For shock protection level 1, 100-man shelters, the most economical shelter was the one-story, concrete cubicle for pressures up to 50 psi. For pressures from 50 to 100 psi, the costs for the one-story concrete cubicle and one-story concrete arch (with vertical end) were comparably low. For pressures from 150 to 300 psi, the costs were comparably low for three structures: the one-story concrete cubicle, the two-story concrete cylinder, and the one-story concrete cylinder.

For shock protection level 3, 100-man shelters, the most economical shelter was the one-story concrete cubicle (7 ft-bay) for pressures up to about 50 psi. For pressures from 50 to 100 psi, the costs for the one-story concrete cubicle and the one-story concrete arch were comparably low. For pressures from 150 to 300 psi, the costs were comparable for three structures: the one-story concrete cubicle, the two-story concrete cylinder, and the one-story concrete cylinder.

For the Havers and Lukes study for 500-space shelters, no shock isolation, the most economical shelter was the one-story steel cubicle for pressures of 10 to 25 psi. For pressures from 25 to 50 psi, the most economical shelter was the one-story concrete cubicle. For pressures from 100 to 300 psi, the most economical structure was the two-story concrete cylinder. Its nearest competitor was the one-story concrete cylinder.

For the 500-space shelters with shock protection level 1, the most economical shelter was the one-story steel cubicle for pressures of 10 to 25 psi. For pressures of 25 to 50 psi, the most economical shelter was the one-story concrete cubicle. For pressures from 50 to 100 psi, the most economical structures were the one-story concrete arch and the one-story concrete cubicle. For pressures from 100 to 350 psi, the most economical shelters were the one- and two-story concrete cylinders.

For the 500-space shelters, shock protection level 3, for pressures of 10 to 25 psi, the most economical shelter was the one-story steel cubicle. For pressures of 25 to 50 psi, the one-story concrete cubicle was the most economical. For pressures from 654 to 350 psi, the most economical shelter was the two-story concrete cylinder.

For the Havers and Lukes study of 1000-man shelters, no shock isolation, the most economical shelter was the one-story structural steel cubicle for pressures from 10 to 20 psi. For pressures from 20-50 psi, the most economical shelter was the one-story concrete cubicle. For pressures from 50 to 350 psi, the most economical shelter was the two-story concrete cylinder.

For the same study and conditions but shock protection level 1, the most economical shelter was the one-story structural steel cubicle for pressures from 10 to 20 psi. For pressures from 20 to 50 psi, the most economical shelter was the one-story concrete cubicle. For pressures from 50 to 100 psi, the most economical shelters were the one-story concrete arch and the one-story concrete cubicle. For pressures from 100 to 350 psi, the most economical shelters were the one- and two-story concrete cylinders.

For the 1000-man shelters at shock protection level 3, the most economical shelter was the one-story structural steel cubicle for pressures from 10 to 20 psi. For pressures from 20 to 50 psi, the most economical shelter was the one story concrete cubicle. For pressures from 50 to 350 psi, the most economical structure was the two-story concrete cylinder.

As will be made clear in the Summary section (2.5), IITRI studies result in the lowest costs for any of the serious blast shelter studies. Goen (1966) has attempted to explain their low costs within the following argument: The IITRI studies appeared to be a significant breakthrough in shelter methodology, utilizing thinner concrete elements with higher strengths of concrete and reinforcing steel to produce a considerable reduction in the costs of hardening. Systematic effort was exerted to optimize the costs of the shelter elements. However, the extensive and careful control which the contractor would have to exercise might well tend to offset the savings from higher-strength concrete. Since no shelters were actually ever constructed and tested using the IITRI designs, the true cost figures and the actual ability of the structures to perform as designed were obviously never determined.

No attempt at all was made to include the effect of earth-arching. It would substantially reduce costs of shelters with long narrow bays or horizontal cylindrical shelters.

2.1.5 University of Arizona Studies - Harrenstein, et al., A Study of Counterforce Defense System Methodology Applied to Tucson, Arizona and Environs, June, 1964; H. P. Harrenstein, et al., Cost Studies in Protective Construction Systems, Jan., 1965; H. P. Harrenstein, A Risk-Oriented Solution for a Target Community, in Protective Structures for Civilian Population, April, 1965; H. P. Harrenstein, et al., Yielding Membrane Elements in Protective Construction, May, 1965

In the early 1960's, Harrenstein and coworkers (Harrenstein, et al., June 1964, Jan. 1965, Apr. 1965, May 1965) at the University of Arizona developed several novel concepts for a blast shelter design to protect the population of Tucson which would be a major target in a potential nuclear attack because of its SAC base and contingent of Titan ICBMS. The main shelter concept was the utilization of a network of steel conduits buried under 5 feet of earth beneath the city. Other unusual concepts were the employment of yielding membranes to be used either for roofs of shelters or to serve as blast doors.

In Harrenstein, et al. (May, 1965), there is an extensive theoretical discussion of the use of yielding membranes to serve as walls or roofs of blast shelters. Argument was made to promote the use of curved shell structures, which resist loads by either developing uniform tensile or compressive stresses, dependent on the configuration. The steel shell is best in tension and the concrete shell is best in compression. Because compressive funicular shells with low thickness to curvature ratios may buckle in overload, it is probably better to avoid the potential problem by insisting on the use of tensile funicular shells.

Although extensive structural analyses for curved shells is included in this report, no specific total shelter structure is presented and no cost analyses were undertaken.

In the study of costs (Harrenstein et al., June 1965) costs were estimated for a flexible structure for several different types of soil conditions. This system was composed of a network of interconnected buried conduits plus standardized entrance modules. Entrance modules could be either steel arch pipe, reinforced concrete box, or concrete tube, dependent on soil conditions and construction economy. The main structure could be constructed either from reinforced concrete or corrugated steel pipe.

Also considered in this report are designs of reinforced concrete structures for Tucson, Arizona and Houston, Texas, capable of housing 5000 or 9000 occupants and designed to withstand either 10, 30, or 100 psi. In general, the major structural concept called for the appropriate number of buried concrete-box components. Costs were presented for each specific design overpressure for unit shelters. Final tables of costs for the Houston and Tucson systems were presented giving total costs for the number of shelters necessary to protect the total population for each city. Included in these final tables were not only structural costs but also environmental costs. These cost data are not analyzed here in depth but costs/space are summarized in Table 2.4.

Finally, a unique and novel concept was proposed for large shelters (4500 occupants). The design was based on the use of clustered vertical cylinders using large steel plates as top and bottom structural members. The total floor area was 50,400 ft^2 and the gross volume was 631,000 ft^3. Based on a capacity of 4500 persons, a gross floor area of 11 ft^2/person, and a gross volume of 156 ft^3/person was allowed. Utilities, sanitation facilities, mechanical and electrical equipment and other advanced habitability items were provided. The shelter was designed for dynamic behavior based on ultimate strength theory and theoretical blast loadings consistent with a peak incident shock of 60 psi. The system cost, including main structure, extensive habitability items and provisions and allowance of 15% for profit, 10% for insurance and overhead, and 5% for design fees, was $305/space in 1965, or $1105/space in 1982.

Table 2.4. Blast Shelter System for Houston and Tucson

City	Reinforced Concrete Boxes		
	Pressure (psi)	Cost per Space (late 1964 price)	Cost per Space (1982 price)[a]
Houston	10	$110	$399
	30	134	485
	100	186	674
Tucson	10	108	391
	30	134	486
	100	178	645

[a]Prices adjusted to 1982, using Engineering News Record Index, which may slightly overestimate 1982 costs because some habitability items have not increased in price as fast as have building costs.

In the report by Harrenstein (June, 1964), the objective was to develop procedures and methodologies for evaluating local hazards and to determine the potential civil defense countermeasures for cities associated with military targets, with Tucson as the pilot subject. The first portion of the study is general and non-technical and contains several cost analyses of candidate shelters while the appendices are directed towards technical details of structural loadings and engineering design and analysis. Topics discussed include: (1) probability or reliability of magnitude of effects from nuclear blasts; (2) ground motion and soil structure interaction; (3) prediction of initial radiation; and (4) prediction of close-in fallout. In the topic on soil-structure interaction, discussions are presented on the concepts of soil-structure interaction pressures for several types of buried structures -- rigid buried, rigid-flexible buried, and flexible buried. A theoretical section on behavior of flexible membranes under load is also included.

In Harrenstein's June 1964 report, costs are presented for several different types of blast shelter designs, varying from family units to those capable of housing thousands, with the number of various shelters adjusted to those required for protecting the population of Tucson. Five small rigid shelters designed for relatively low overpressures (0-30 psi) are presented along with information on three large shelters, a rigid concrete unit structure for 1000, a flexible community unit structure for 4500, and a buried steel conduit for housing the entire metropolitan population of Tucson.

The cost factors considered in these analyses are quite extensive, including excavation, concrete work, reinforcing and structural steel, sealer coat, ventilation, electrical, sanitation, and hotel accommodations. However, no provisions for contractor O, P, and C were made. In Table A-6 are listed the various percentages which each cost factor contributes to the total costs. A summary is shown in Table 2.5 of the costs of extending the use of each type of shelter to the total 1964 population of Tucson. The least expensive of these proposed shelters is the buried corrugated steel conduit.

Table 2.5 Shelter Costs from University of Arizona Study

	Persons per Shelter	Unit Cost (1964$)	Total Units 1973 Population	Total Cost[a] (1964$)	Cost per Person 1964$	Cost per Person 1982$	Pres. (psi)	Space per Person (ft^3)
Industrial culvert, family	3.12	11,816	149,520	1,766,526,385	3799	13,764	ns	400
Flat plate roof, family	3.12	9,658	149,520	1,443,878,475	3105	11,250	ns	615
Domed roof, family	3.12	8,891	149,520	1,329,243,370	2859	10,359	ns	400
Dished roof, family	3.12	10,901	149,520	1,629,789,200	3505	12,699	ns	400
Concrete box, family	3.12	6,138	149,520	917,638,475	1973	7,149	30	70-80
Rigid, community	1000	280,338	465	130,357,340	280	1,014	-	-
Flexible, community	4500	1,427,119	114	162,448,956	349	1,264	ns	-
Buried conduit	465,000	124,167,392	1	124,167,392	267	967	ns	-

[a]Cost for sheltering 465,000 people

The shelter systems based on small units seem to require excessive costs. Part of these high costs is probably due to the fact that no correction was included for use of the concepts of mass production and economy of scale. Another reason for the high costs may have been an excessive allocation of space for each occupant. However, ft^2 and ft^3 of space per occupant were not adequately described in the designs. When the blast shelter system was based on units handling thousands of occupants, the cost/space was decreased dramatically and became more in agreement with the very large shelter systems designed in the costs study (June 1965).

Finally, the projected 1982 cost/space for the extensive buried conduit system seems somewhat excessive. Although economy of scale may act as a m derating influence on the cost of such a system, the provision of extensive covered walkways from points of high population density for the system would seem to allow for much more than the standard 10 ft^2/person and 80 ft^3/person. Thus, a considerable portion of the $967/space was probably allocated to long entrances/exits not normally considered in shelter for 10-1000 people. Thus, even though the corrugated culvert shelter was shown to be the least expensive, it might have been even more attractive if a more reasonable cost/space number had been reported.

2.1.6 Ulrich Luscher - Behavior of Flexible Underground Cylinders, 1965

This study (Luscher, 1965) described the elastic behavior and failure conditions for underground flexible cylinders, with specific analysis of the possibilities of arching, deformation, and buckling. A comprehensive theory of buckling of underground cylinders was discussed. No new data were presented in the report; thus, analyses and conclusions were based on a large body of experimental and theoretical work in the literature.

An informative analysis of the possible structural failure modes of a flexible cylinder buried to a depth of at least one diameter was conducted. These modes of failure were: (1) joint failure, (2) excessive

deformation resulting in cave-in of the crown, (3) elastic buckling of the tube wall due to hoop stresses which are excessive for the existent tube rigidity and lateral support, and (4) yielding of the tube wall caused by excessive hoop stresses, leading to general crushing. Yielding may be preempted by plastic buckling due to a loss of wall rigidity.

The failure due to excessive deformation can generally be avoided by achieving appropriate backfill on the sides of the cylinder. Another method of avoiding deformation is to alter the cross section of the cylinder by vertical ellipsing.

Joint failure can generally be prevented by constructing joints with strength equal to or greater than that of the wall. An extremely effective method of increasing resistance to buckling is to utilize corrugated cylinders.

This article was reviewed to introduce further information about the utilization of corrugated culverts as blast shelters and modes of hardening. No cost analyses were discussed by Luscher.

2.1.7 R. A. Krupka, Final Report on Shelter Costs, 1964

R. A. Krupka (1964) attempted to develop a simple cost function for general blast shelter design. As the basis for the study, costs, overpressures, space allocations, and other significant parameters were extracted from several previous shelter design studies. Previous efforts to evolve models for optimizing shelters had been focused on minimizing expected casualties from an attack by some arrangement of distribution and quality of the shelters for the population to be shielded. The degree of optimization was usually expressed in cost-effectiveness terms such as dollars/life saved, dollars required to force a particular level of attack, etc. Regardless of the type of cost-effectiveness measure used, it is generally necessary to know the cost of shelters as a function of hardness. Krupka's effort then was to develop such an expression, and there was no claim that the expression being developed was a general cost expression for blast shelters given in terms of all the major parameters.

The issue of dependence of costs on total shelter occupancy was addressed in a cursory way by plotting cost data for shelters varying in occupancy from 100 to 1000 spaces. It was concluded that 100-man shelters cost about twice as much per person as 500- to 1000-person shelters.

Twenty-four different shelters were considered in this study. As noted before, the shelter designs were not developed by Krupka but rather were taken from several other previous studies. Costs for main structure and entranceway were included for all shelters while costs for mechanical-electrical, sanitation and water, habitability items, and control package were included in only a few studies. (See Table A-7).

For the purposes of comparing costs vs overpressure for the different shelters, Krupka extracted costs for the main structure and entrance, adjusted them for 60% overhead, profit, and contingencies and expressed them all at cost/ft^2 of shelter space. These costs were plotted in a log-log relationship to allow for extraction of the functional cost/overpressure relationship. Apparently, it was the intention of Krupka to choose a wide diversity of designs for his analysis. Shelter occupancy varied from 5 to 8000 (with the exception of one shelter in a deep rock tunnel designed for 4,000,000 people), while overpressures ranged from 5 to 1500 psi. The result of such a diverse set of shelters was a cost/ft^2 band that varied from \$1.5 to \$12/ft^2 at very low overpressures and from \$30 to \$80/ft^2 at 1500 psi. (1964 dollars)
Two equations were thus derived from the band:

$$c = 9.3\ p^{0.31} \text{ upper limit} \qquad (1)$$
$$c = 1.8\ p^{0.4} \text{ lower limit,} \qquad (2)$$

Where c is cost in 1964 dollars/ft^2 of space.

Two compromise equations were derived to take into account differences at wide pressure variations. These were:

$$c = 40 + 34\ p^{0.34} \text{ at pressures to 60 psi} \tag{3}$$

$$c = 3.2\ p^{0.62} + 34\ p^{0.3} \text{ for higher pressures} \tag{4}$$

Where costs were converted to 1964 dollars/person. A final compromise equation was proposed:

$$c = 50 + 20\ p^{0.5}, \tag{5}$$

which represented the main values fairly well at lower overpressures but probably gave high values for the cost at large overpressure, even with all the uncertainties. It should be stressed that this equation estimates costs in 1964 dollars. The constant was included primarily to represent non-pressure-dependent items, which Krupka called fixed costs. These habitability items were estimated, in 1964 dollars, to have the following ranges:

Mechanical-electrical	\$25-75/person
Sanitation and water system	\$5-15/person
Habitability items	\$10-20/person.

Finally, it was assumed that the mean value of \$75 (1964 dollars) could be represented by a fixed cost of \$40-50/person at 60 to 100 psi.

Admittedly, these relationships are very limited in their utility. The equations 3, 4, and 5 are compromise expressions giving mean values for a wide band of uncertainty. The provisions for fixed costs (habitability items) are argumentative at best and contain no allowances for extensive hardening of supporting systems and shock isolation procedures that would be required at high pressures. Other limitations are:

(1) Land costs are not included.

(2) No inclusion of costs savings due to efficient planning, phasing, mass production techniques, or standardization.

(3) The space allocation is arbitrary. Also, as noted in the beginning, the equations have no utility for predicting costs as a function of type of design or occupancy.

2.1.9 Carsten Haaland, Systems Analysis of U.S. Civil Defense Via National Blast Shelter Systems, 1970

In his study (Haaland, 1970) on alternative blast shelters systems, Haaland included a section on estimating costs for long, tubular blast shelters. He extended Krupka's arguments to cost equations for both entrances and the main structure. Equations were developed to estimate cost/space as a function of either space or overpressure. The data for which empirical relationships were obtained were taken from the Ammann and Whitney (1963), GATC(1963), and Longinow & Stepanek (1968) studies. An equation of the form

$$C_s = C_e/S + C_L/N$$

C_s = cost/space

C_e = Cost of ends

C_L = cost/unit length

S = total number of spaces

N = number of spaces/unit length

was used to estimate cost/space for various spaces using GATC and A&W

data for shelters with fewer spaces. Equations of the form $C = A+BP^D$ were developed to estimate cost/space for A&W and GATC shelter for 1000 spaces as a function of overpressures up to 1500 psi. For fitting the data of Longinow & Stepanek and Fitzsimmons for overpressures from 10 to 1000 psi, the most accurate equation for austere conditions was:

$$C = 72 + 5p^{0.83}. \qquad (6)$$

(Includes only costs for pressure-dependent items). In 1982 dollars dollars, this equation is $C = 175 + 14.66\ p^{0.83}$.

A fixed cost of $300/person was added to the austere costs to arrive at the barely comfortable costs.

2.1.10 Charles Curione, Cost Trends of Mass Production As Applied to 5-10 Psi Shelters

The purpose of this study (Curione, 1967) was to determine the cost reduction potential of mass production techniques applied to construction of 5-10 psi shelters. Analyses were conducted to compare costs of conventional onsite construction with construction of equivalent structures utilizing mass-produced structures or structural components. All costs were adjusted to the year 1966 by applying the Engineering News Record Index.

Curione indicated many of the problems encountered by a reviewer who attempts to collate the cost data from widely diverse studies of blast shelter costs. Negative factors in collating the literature include:

(1) Structures often were a one-time design or construction task to serve a specific function;

(2) Costs were often a secondary consideration;

(3) Contracts were often awarded on a lump-sum or cost-plus basis and many changes were allowed after construction started, significantly affecting project cost;

(4) Many of the design studies on shelters were not based on common design criteria. This arose because there were many developers of shelter design with varied levels of experience.

Curione analyzed several factors which might significantly affect shelter costs when mass production was utilized. These included cost of materials, modular units, standardization of components and subassemblies, optimal use of work crews, etc. He concluded that the savings are probably in reduced on-site construction activity, because the plant labor savings in mass-produced material may be totally offset by transportation and handling costs. Based on the review of shelter costs, Curione suggested that a good "rule of thumb" for allocating shelter costs is that the basic structure cost (entrance, excavation, and backfill) contributed about one-half of the total shelter costs. This was based on the definition of total cost (direct and indirect), including costs for contractor overhead, profit, and contingencies, design fee, mechanical and electrical equipment, and the basic structure with entrance, excavation, and backfill. This total cost did not include shelter furnishings (bunks, benches, etc.), control administration costs, and land costs.

The costs are shown in Table 2.6 for the various shelters chosen by Curione for his study. It should be stressed that these shelters were taken from varous literature references and were not designed by Curione. The cost/space was adjusted to 1982 prices by using the Engineering News Record Index and was also adjusted to include 20% O,P,C. Both direct and indirect cost factors were included as noted above (also see Table 2.1).

The major conclusions in the Curione study are:

(1) Savings of 2-10% might be possible when mass production techniques are applied to shelter building programs if a sufficiently large volume of work is generated.

(2) Transportation costs become critical for mass production techniques applied to concrete shelters, so that often the advantages of mass production are lost if the distance from processing plant to shelter site exceeds 200 miles (in 1967).

(3) Costs for the basic structure, entrance, and earthwork constitute 48-50% of the total shelter costs. The remainder of the cost is due to mechanical and electrical, contract administration, and contractors' overhead, profit, and contingencies.

Table 2.6 Cost of Shelters from Curione Study (1967)

Shelter Type[a]	Number of Persons	Cost/ ft^2	Cost per Person[b] (1966$)	Cost per Person 10%,O,P,C (1982$)	Cost per Person 20%,O,P,C (1982$)
CR	100	37.50	375	1302	1420
MA	100	33.60	336	1167	1273
CR	100	25.08	251	871	950
CR	100	27.61	276	959	1046
CR	170	28.30	283	983	1072
CR	300	28.93	289	1005	1096
CR	350	21.45	215	745	813
CR	350	22.22	222	772	842
CR	500	20.46	205	710	775
CR	500	21.67	217	752	820
CR	550	19.80	198	688	751
CR	550	25.60	256	889	970
CR	550	19.91	199	691	754
-	600	19.30	193	670	731
CR	1000	17.30	173	601	656
CR	1000	19.03	190	661	721
CR	1000	20.13	201	699	763
-	1100	18.70	187	649	708
-	1100	22.44	224	779	850
-	1100	18.48	185	642	700
CR	5000	14.74	147	512	559
CR	5000	17.27	173	600	655
CR	5000	14.63	146	508	554
CR	5000	16.61	166	577	629
-	22,000	13.10	131	455	496
CR	30	47.60	470	1632	1780

[a]CR = Rectangular reinforced concrete; MA = Multiple arch

[b]Space per occupant = $10ft^2$

(4) The cost/occupant for shelters protecting against 5-10 psi decreases sharply as the number of spaces increases from 100 to 700, but does not change significantly above 700 spaces.

Detailed construction drawings are not presented in Curione's report, nor is there any information concerning costs of concrete, interior and exterior walls, roof, labor, etc.

2.1.11 Bechtel, Final Study Report for Protective Blast Shelter System Analysis, 1967

The purpose of this report (Bechtel, 1967) was to study the feasibility of providing a 25-psi blast shelter system for the entire population of Providence, Rhode Island. The distribution of shelters throughout the city was to be compatible with a plan that would permit loading by walking access within 30 minutes after an alert. Space allotment was 10 ft^2 per sheltered occupant. Some conceptual factors to be considered to minimize costs were dual-purpose-use of public-owned land, and construction problems and legal factors affecting site availability.

Cost estimates for newly-constructed single- or dual-purpose shelters were based on buried, rectangular, concrete-box structures which were similar to the 25-psi shelter garage in OCD Standard Design Series G35-2, April 11, 1962 (OCD, 1963). See also S-55 and C45 reports in that series. The following cost factors were included in the estimates (prices for construction items were in-place costs, including allowances for material, labor, overhead, and profit): (1) Site survey and preparation, (2) excavation and backfill, (3) dewatering, (4) relocation of buried utilities footings and concrete-box main structure, (5) entrance ramps, (6) blast doors and valves, (7) ventilation system, (8) water and sanitation, (9) emergency diesel generator and fuel tank, (10) electrical system, (11) site drainage and landscaping, (12) fees for construction permits, and (13) overhead and profit. Not included were other fees and taxes associated with construction, provisions for food, medical facilities, and communications/monitoring equipment, air conditioning, or maintenance of completed shelters. Prices reflected a nationwide mean adjusted to Providence, RI as of September 30, 1966.

Constructic· costs were based on awarding a minimum of five structures to any one ɛractor, thus allowing for a learning factor.

All of the shelters considered in this study were of relatively large size. Cost/space was estimated for the various capacities for both single-purpose and dual-purpose use (see Table 2.7). The single-purpose use is of most interest to this review; thus, we will not discuss dual-purpose use (except it is interesting to note that the costs increase for dual-purpose use was usually 1-10% higher than single- purpose cost).

Table 2.7. Shelter Costs Single and Dual-Purpose Use

Capacity	1966 Cost,$		1982 Cost,$	1966 Cost,$		1982 Cost,$
	Single-Purpose	Per Occupant	Per Occupant	Dual-Purpose	Per Occupant	Per Occupant
2000	456,500	228	803	-	-	-
6000	1,350,)00	225	792	1,528,300[a]	255	898
8500	1,704,500	200	704	-	-	-

[a]Recreation Center

Most cost studies agree that the cost per occupant varies inversely with shelter size fcr a give.. type of shelter configuration. The rate of decrease is quite rapid as shelter sizes vary from 100 to 5000 spaces, approaching an asymptote for shelters greater than 5000 spaces. Tne cost savings are realized because of an increased volume to surface area as well as consolidation of required services when shelter capacity increases.

2.1.12 Longinow and Stepanek, Civil Defense Shelter Options for Fall-out and Blast Protection (Single-Purpose), 1968

The purpose of this study (Longinow & Stepanek, 1968) was to develop data on shelter concepts, costs, and protective capabilities of shelters capable of being utilized in shelter complexes at appropriate locations. Designs and costs were considered for structures capable of withstanding 0, 10, 20 and 30 psi overpressure at three burial conditions for six different costing options. The types of structures were: (1) rectangular reinforced concrete; (2) concrete and timber; (3) reinforced concrete arch; and (4) steel arch. The three kinds of burial were (1) location below grade, (2) balance cut and fill, and (3) location at grade. There was wide variation in the six cost options, which can be summarized as follows (see Table 2.8).

Table 2.8 Cost Factors Considered in Longinow/Stepanek Options

Option	Site Preparation	Earthwork & Structural	Mechanical	Electrical	Architectural	Entranceway	Service Road and Parking Lot	Contractor's Overhead, Profit & Contingencies
1	X-A	X	0	0	0	X	0	X
2	X-A	X	A	A	0	X	A	X
3	X-A	X	C	C	X	X	A	X
4	X-C	X	0	0	0	X	C	X
5	X-C	X	A	A	0	X	C	X
6	X-C	X	C	C	X	X	C	X

NOTE: X = included
0 = excluded
A = austere, see text
C = comfortable, see text

The consideration of all the structural designs, burial options, and optimal equipment led to 834 separate design cases. References to Longinow and Stepanek's original study will show that the most economical type of structure is dependent on the type of burial, as well as space, cost option, and pressure.

For the designs of Longinow and Stepanek with no shock isolation, prices updated to 1982, burial condition 1, (below grade) and 10 to 30 psi, for 500 spaces, the most economical shelters are the steel arch and the reinforced concrete arch. For the same conditions and 1000 spaces, the most economical shelters are the rectangular reinforced concrete and the reinforced concrete arch. For the same conditions and 5000 spaces, the most economical shelter was the reinforced concrete arch.

2.1.13 Holmes and Narver - Parametric Study of Small Personnel Blast Shelters, 1969

This study (Shimizu et al., 1969) focused on analyzing the costs of several blast shelter designs based on three parameters (shelter capacity, blast overpressure, and type of construction). Preliminary costs of three types of shelters (rectangular concrete, concrete arch, and steel arch) were given based solely on two cost factors, shelter structure and earthwork. Cost data were presented in the form of total shelter costs as a function of shelter spaces for the three types of shelters studied (See Table A-10).

Because of the very limited cost factors included in the original estimates (see Table 2.1), it was necessary to estimate several necessary improvements to the shelters to bring the design and outfitting of the shelters up to the level of design used to compare the costs of various other shelter designs included in Appendix A. Entrance costs were estimated by allowing for 25% of basic costs (a very conservative figure) to be charged to entrance construction. Mechanical and electrical costs were estimated, as they were for other studies, by assuming that they amounted to about 25% of basic costs (earthwork, shelter structure, and entrance/exit). Estimates for shock isolation were made

only for shelters at overpressures of 50 psi or greater and were obtained from the arguments of Ammann and Whitney for levels 1 and 3. The costs so obtained were adjusted to 1982 prices using the Engineering News Record Index and were finally adjusted for 20% overhead, profit, and contingencies.

These costs are high because the original costs for structure and earthwork were high so that additions at 25% for entrance and mechanical and electrical were also higher than for other cost studies.

This report contains some very interesting general comments about generic types of shelter designs. These arguments are summarized as follows. Concrete rectangular shelters with flat horizontal roof and flat vertical walls resist blast loading by developing bending or combined bending and compression stresses. Compared to arched cylindrical designs, the rectangular shape gains little from participation of the soil in transmitting blast-induced pressure. It was stated that rectangular shelters are not efficient for overpressures greater than 50 psi because heavier slabs and beams or intermediate supports such as columns and bearing walls are required, with a subsequent reduction in space. These conclusions agree with the findings of the IITRI studies. For low pressures, however, the rectangular shape provides maximum useable space, is the simplest to construct, is the most adaptable to forming, and is particularly suited for design where relatively short roof spans are needed.

Fully-buried semicircular metal arches, of the multiplate design, have been successfully blast-tested for blast loads from nuclear explosions in the 100 Kt range at pressures of 25 to 50 psi for no reinforcement and for 75 to 100 psi for steel rib reinforcement. Based on conventional stress analysis, such structures are not predicted to withstand significant overpressure. It is believed that the shape of the arch and its flexibility allows the metal arch to resist blast pressures due to the favorable phenomenon of earth arching.

Semicircular, reinforced concrete arches do not undergo deflections like those experienced by the flexible metal arch, thus they are not as favorably affected by soil-structure interaction. A reinforced concrete arch with 8-in. wall and 16-ft span has been successfully tested at

pressures up to 200 psi. Although the reinforced concrete arch is one of the most blast-resistant designs, considerable costs can be incurred in the forming of curved concrete surfaces. Forming problems are significant for small shelters, but become less significant as shelter capacity increases. Uninhabitable space in arch or cylindrical structures can be used for storage and equipment.

In general, flexible cylindrical and ellipsoidal structures in granular soil are very effective in resisting blast loading because of soil-structure interaction.

At low overpressure, the rectangular concrete shelter costs the least. At 25 psi there is a trade-off. For less than 25 occupants, the concrete rectangular shelter is the least expensive. For the higher overpressures the concrete rectangular shelter becomes uneconomical so that the shelters of choice are the concrete arch type. At 100 psi overpressure for less than 25 occupants, the metal arch costs slightly less than the fully buried concrete shelter. For more than 25 occupants, the reinforced concrete arch is much cheaper.

2.2 SMALL-GROUP OR FAMILY-SIZED SHELTERS

As is evident from the previous reviews, the bulk of design efforts for blast shelters, particularly those dealing with cost optimization, have been focused on shelters for groups of 100 or more. There is, however, limited literature on single-family shelters with much of it associated with vendor brochures or with articles in general civil defense magazines (<u>Protect and Survive Monthly</u> - March 1981, April 1981, October 1981, March 1982; <u>Journal of Civil Defense</u> - No. 4, 1969, No. 4, 1980, etc.). Some of these small shelters will be briefly reviewed here to provide limited information on the types available and the associated price ranges.

2.2.1 Colvic Fiberglass Shelter.

Colvic Nuclear Shelters of London, U.K., offers a fiberglass shelter with 0.5- to 1-in. wall thickness designed for 15-psi overpressure. This modular unit is capable of protecting 4-5 persons at a cost of about 7000 British pounds ($11,200 in 1982 U.S. dollars) which amounts to $2240/person (including installation costs). This unit is outfitted with a blast door and ventilation with appropriate filters. Costs do not include hotel accommodations, food and water, etc.

This cylindrical tank shelter was described in some detail in the March, 1981, issue of Protect and Survive Monthly. Suggested installation conditions were burial 4 ft below ground and encasement in 10 in. of steel-reinforced concrete prior to covering. When installed, the shelter is supposed to provide a protection factor of 4000 and to resist 15 psi overpressure.

In the ventilation system, the intake was designed so that air is drawn upward, to decrease intake of radioactive dust. Any dust entering the system would be collected on standard replaceable filters.

The use of spring-mounted beds was studied and found to be too costly. Present bedding is based on hammocks in combination with a spring-supported floor for protection against ground motion. The furnishings are sparse, consisting of a small table and a cupboard for utensils. The space under the floor is reserved for a waste holding tank and emergency food and water.

As described in Protect and Survive Monthly (April 1981), the MK II version of the shelter was blast-tested up to 50 psi at the appropriate distance from a conventional 500-ton explosion. At the 50-psi overpressure level, the structural shell incurred one small corner crack, structurally insignificant, after bending down 2 inches under the blast load. Although the shell of the structure underwent violent movements, it was concluded that any occupants would have remained unharmed. The blast valves in the air intake system functioned well, reducing the outside pressure to about 0.25 psi. Because of the spring-mounted flooring, interior items were relatively undisturbed.

Major detrimental effects were that the air intake pipe and outlet pipe were stripped of their protective hoods by the force of the explosion. Measures for dealing with protection of ventilation shafts are suggested in the second part of this report in the discussion of corrugated culvert shelters. (Section 4.1.3).

2.2.2 The Egg

Biosphere Corporation in the U. S. has for a number of years offered for sale to the general public a modular family shelter called "The Egg." This shelter described in Protect and Survive Monthly, March 1982 is constructed from reinforced fiberglass and is offered as both a nuclear fallout shelter and a subterranean vacation home capable of accommodating up to six people. The Egg originally was quoted at $30,000 (1982), completely installed, based on the condition that the company handles all installation, landscaping, etc. Standard equipment and available options are listed in Table 2.9.

"The Egg" is designed for clustering so that small communities can be sheltered. In the event of blockage of the main door, an emergency door is provided, consisting of an overhead hatch covered by four feet of sand in a cylinder reaching to the surface. For an emergency, the hatch is removed and the sand, which flows readily, falls into the Egg, allowing quick egress.

The shell is constructed from a 1-1/4-in.-thick fiberglass sandwiched wall having a rigid foam core. The wall gains strength both from its thickness and the elliptical form. Attenuation of radiation is provided by burial under about 4-1/2 ft of earth.

The cost of $30,000 for protecting 4-5 people in a modular unit (>$6000/occupant) would appear to be quite excessive. There are recent indications by the manufacturers that if a significant market develops for this shelter, much of the initial capital cost can be recaptured and the price of the modular unit may decrease to the $20,000 range. This is still high compared to other modular units, but it should be noted that the Egg has a high level of habitability items.

Table 2.9 Equipment for "The Egg"

STANDARD EQUIPMENT

SHELL WALL
- Constructed with fire retardant, fiberglass reinforced plastic, PVC foam core sandwich

ENTRY PACKAGE
- Stair companionway with ground-level access door.
- Vestibule

STANDARD INTERIOR
- Bulkheads
- Water-tight door
- Shelves
- Drawers
- Seats with cushions - twin berth
- 4 berths with cushions
- 2 tables
- Kitchen sink
- Bathroom sink with shower

WATER SYSTEM
- Pressurized filtered water in kitchen with manual backup
- Manual foot pump for shower, 470-gal water storage tank

SANITATION SYSTEM
- Vacuum-assist toilet, operates automatically with floor pedal
- 600-gal waste holding tank

KITCHEN ACCESSORIES
- (2) 12-volt cooking units

ELECTRICAL SYSTEM
- (3) 105 amp/hr storage batteries
- 5-circuit, marine-grade fuse panel
- Marine-grade, double-insulated wiring
- 1 fluorescent light
- 3 wall-mounted reading lamps
- Marine-grade water system pump
- (2) 12-volt electrical outlets
- Pedal-driven battery charger

VENTILATION SYSTEM
- 6" PVC tubes with screening and filtering
- (2) 12-volt ventilation fans

ENTERTAINMENT PACKAGE
- 12-volt AM-FM radio/cassette player

AVAILABLE OPTIONS

- Freeze-dried food assortment
- 110-volt umbilical power package
- 70-gal extra water storage
- 12-volt solar charger system
- C.B. radio transmitter/receiver
- Carpeting
- First aid kit
- Custom-tailored linens
- Emergency exit ladder
- Dosimeter
- Geiger counter
- High-level ion counter

2.2.3 Steel Modular Unit: Survival Module Construction, New Forge Works, Great Britain, Protect and Survive Monthly, Oct., 1981

In the October 1981 issue of Protect and Survive Monthly, a steel modular unit called Survival Module Construction designed by a company New Forge Works, 1981) in Great Britain, was described. Offered for family units, the shelter includes the following package: Swiss VA20 ventilation unit, blast valves, blast and airtight entry/exit doors and such accommodations as bunks, timber-lined living area, toilet, shower, sump pump, storage area, 12 V lighting system, wash basin, and water supply (1400 liters for drinking, 350 liters for sanitation). The module can be protected by reinforced concrete to the level of hardness desired by the customer. Emergency escape is provided by a hydraulic door capable of lifting 5 tons of soil or debris.

The cost in 1981 was quoted at 8500 British pounds for a family unit. Based on an exchange rate of $2.13 U.S. dollars/British pound, this gives a 1981 price in the U.S. of $19,550 or, for a family of 5, a cost/occupant of $3910. However, there have been recent dramatic gains made by the dollar in the exchange market, quoted at about $1.6/Pound as of December 29, 1982. Because of this, this shelter would cost $13,600 in U. S. dollars, or $2720 per occupant as of December, 1982.

2.2.4 Sawyer Shelter: H.A. Sawyer, Economy Blast Shelter, August 1969

In 1969, H. A. Sawyer (Sawyer, 1969) proposed a simple do-it-yourself reinforced concrete shelter to protect a family against over-pressures up to 30 psi. This shelter was designed to be constructed in the immediate vicinity of the basement of the family home, such that a door was provided for access to the basement. An optional manhole in the ceiling for emergency exits was suggested.

The main structure was constructed from solid concrete blocks, 8 x 8 x 16 in., stacked in a circular fashion in progressively smaller circles to resemble the shape of one-half of an egg. The blocks of the first course were laid on a thin mortar bed on polyethylene with the long dimension in the radial direction, for footing. The roof was to be

poured in place with concrete (3000 psi) and appropriately reinforced with steel bar. The shelter, 10-ft-ID at the bottom and 8-ft-ID at the top, contained 10 courses of blocks to give a height of about 6 ft, 8 in. and could sleep six people.

Ventilation is provided by an inlet pipe (3-in. galvanized pipe) equipped with a 60 cfm hand-driven blower. The vent should be painted with a heat reflective material and located at a distance from the house greater than the wall height. A filter for use after the blast can be screwed into the shaft. The shelter is also provided with a waste drain pipe. Both the waste pipe and the vent pipe are potentially vulnerable to blast unless corrective measures are taken. The ventilation system can also be criticized because only one shaft is included with the assumption that the door will serve as the air discharge point.

The shelter provides sleeping space for 6 people. Bunks are constructed from 3/4-in. external plywood hung from the roof by eyebolts. The ceiling is to be poured on forms constructed of plywood sheets fitted over the top wall course and supported by 4 x 4 stringers braced by 4 x 4 posts.

The protection factor for this shelter was estimated to be about 1000. This was based on construction adjacent to an exterior wall of a residence, with a hole in the wall for entrance/exit and an optional manhole for emergencies. Roof cover was at least 30 in. minimum -- 15 in. of earth and a 15-in.-thick concrete roof. For houses with basements, the floor level of the shelter is about one foot below the basement floor; for houses without basements, the shelter floor level could be about 3 feet below the floor level of the house, if a proper retaining concrete wall is provided between the shelter and the adjacent residence. The radiation protection assumes some shielding by the residence and shielding by a special wall at the entrance. In the absence of a blast valve or a standard blast door, protection is to be provided by a wooden blast door rolled into place on casters in a light wooden guide across the basement entrance. An additional 8-block emergency barrier can be put in place by the occupants after the blast wave has passed.

Table 2.10 Itemized Costs of the Sawyer Shelter (30 psi)

Construction Factor	Low Do-It-Yourself		High Contractor	
	Cost		Cost	
	1969	1982	1969	1982
Materials	390	1108	390	1108
Skilled Labor - Excavation, Entrance Hole, Mason, Backfill	115	327	250	710
Additional Labor - Carpentry, Ditching, Painting	-	-	250	710
Contractor's Involvement			300	852
	505	1435	1190	3380

The costs of the Sawyer family blast shelter are itemized in a general summary in Table 2.11, with two types of construction, by do-it-yourself or by contractor. The estimate of $600/occupant in 1982 dollars for the contractor-built version is an attractive figure for any kind of shelter offering any level of blast protection at present-day prices (family-size shelter). However, it appears to be a bit conservative. Items which appear not to be adequately covered are: (1) satisfactory ventilation, in that there are not enough shafts provided or the design is vulnerable to blast; (2) proper positioning, design, and drainage of the waste pipe; (3) the function of the entrance to the basement in the presence of blast or fire is questionable; and (4) there is no provision for electrical items. The level of habitability would be classified as very austere.

2.2.5 Plans and Specifications for Family Blast Shelters (30 psi) Emergency Measures Organization, Ottawa, Canada, 1962

In 1962, a detailed description of blast shelter designs capable of withstanding 30-psi overpressure at three conditions of burial (below-grade, partially below grade, and above grade) was published by Canadian authorities (EMO, 1962). The drawings are presented in detailed plan and elevation views. Extensive specifications were given for the following: excavation, concrete work, waterproofing, carpentry, miscellaneous metalwork, mechanical work, and instructions for operating the shelter ventilating equipment.

For this shelter, no cost data were presented; therefore, no comparisons can be made with the costs of the previously-discussed small group shelters.

2.2.6 Summary of Family-Sized Shelters

The cost factors included in the austere and commodious packages for most of these commercially-designed, family-sized shelters are summarized in Table 2.12. For details of the items included in the austere or commodious case, the text should be consulted. Approximate estimates of the cost/space for the various shelters, with austere and commodious cases when available, are given (as $1982) in Table 2.13.

Table 2.11 Cost Factors Included for Small-Group or Family Blast Shelters

Design Study	Site Preparation	Excavation	Backfill	Structural	Shock Isolation	Entranceway	Mechanical	Blast Valves	Electrical	Shelter Furnishings, Cost, & Sanitation	Food & Water	Land Costs	Contractor, Overhead, Profit, &Contingencies	Govt. Supervision	Communications & Monitoring	Architect, Engineer	Bonds & Insurance
Colvic Shelter	X	X	X	X	X	X	X-A	X	X-C	X	0	0	X	0	0	0	0
SMC Unit	0	0	0	X	0	X	X-C	X	X-C	X	H_2O	0	X	0	0	0	0
The Egg	X	X	X	X	0	X	X-C	0	X-C	X-C	opt	0	X	0	opt	0	0
Sawyer Shelter	0	X	X	X	0	X-A	X-A	0	0	X-A	0	0	X	0	0	0	0

NOTE: X = included
0 = excluded
A = austere
C = commodious or comfortable
ns = not specified

Table 2.12 Cost Comparison for Several Family-Sized Shelters

Study	Total Cost Austere Case	Cost/Space Austere Case	Total Cost Comfortable	Cost/Space Comfortable
Colvic (5 spaces)	$8,000	$1,600	$ 9,600	$1,920
SMC (5 spaces)	NA	NA	13,600	2,720
The Egg (6 spaces)	NA	NA	20,000	3,333
Sawyer (6 spaces)	1,435	240	3,380	563

NOTE: NA - Not available

2.3 RECENT STUDIES

2.3.1 Donn Corrugated Culvert Shelters, Donn Blast Shelter Test No. 1 Miser's Bluff Event II-I, March 1979; Donn Blast Shelter Test No. 2, Miser's Bluff Event II-II, March 1979; Blast/Fall-Out Shelter, Dec. 1978

The Donn Coporation (Donn Corp., 1978, 1979) has been the most recent active supporter of the use of corrugated steel culverts for blast shelters. A drawing of the Donn corrugated culvert shelter tested at Miser's Bluff Event II-I is shown in Fig. 2.1. A minimum of 39 inches of soil cover was determined to be necessary to allow development of an effective earth arch. A soil cover of 48 in. was calculated to provide adequate protection against initial nuclear radiation from an airburst of 1 megaton or greater at the 50 psi overpressure range. A compromise value of 42 in. of soil cover was adopted for the non-radioactive test.

The dimensions of particular interest in the Donn design are:

1. The main shelter was fabricated from sectional corrugated plate, 3 in. x 1 in. wide corrugations.

2. There were two, 24-in.-wide plates per revolution, and 7 sections of 24-in. revolutions which gave a main section 168 in. long.

3. Plate thickness was 0.064 in.

4. The entrance shaft was corrugated culvert 120 in. long by 30-36 in. I.D., with thickness of 0.064 in.

5. The base of the entry shaft was a flat steel plate, 0.109 in. thick.

6. The access tunnel was corrugated steel, 30-in.-diameter and 48 in. long, with connections between the entry shaft and one end of the main shelter made by using banded o-ring joints.

7. The ends of the shelter room were constructed from truncated 30° right cones of 0.109-in.-thick steel (tapering from 78 in. to 30 in.). The cones were constructed from three pieces of sheet metal bolted together.

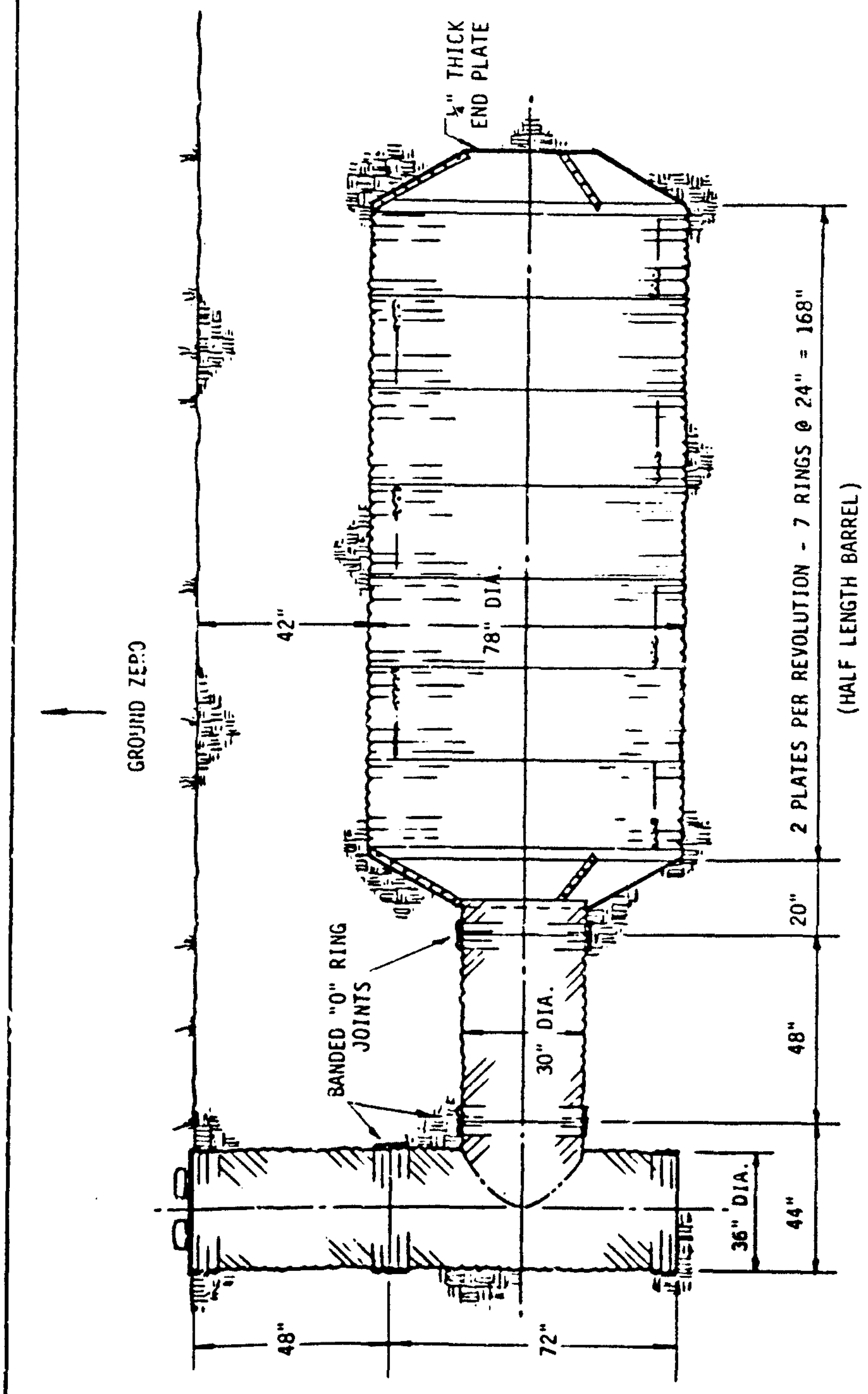


Fig. 2.1 BLAST SHELTER - DONN TYPE II
TESTED AT 50 PSI OVERPRESSURE

MISERS BLUFF EVENT II-I JUNE 28, 1978

8. The cone at the closed end of the main shelter was closed with a flat steel plate, 0.250 in. thick.

9. For 50 and 100 psi tests, blast doors at the top of the shafts were 3/8-in.-thick HSLA (high strength low alloy) hinged to the top of the entry shaft. Blasts valves were 10-in.-diameter, fast-acting spring loaded domes, mounted on the blast door.

The Miser's Bluff Test, Event II-I, allowed the opportunity to test the blast shelters under dynamic conditions for blast effects, which in the initial moments, are good simulations of effects of nuclear detonations. The main purpose of testing the Donn designs was to determine if a light-gage metal shelter, aided by earth arching, would withstand overpressures in the 50-100 psi range.

Shelters designed basically according to Fig. 2.1 and the specifications listed above were tested at 50 and 100 psi levels. Blast doors, valves, and entry tunnels were tested only at the 50 and 100 psi levels. At the 150 psi level only the buried main shelter was tested.

Overall, the main portion of the Donn shelter showed an excellent capability to withstand overpressures up to 150 psi, with the aid of earth arching. For the three pressures, the mode of deformation was as a slightly flattened oval with the shelters being permanently set as ellipses. Some travel of the crown was observed for all three pressures. The most vulnerable aspect of the Donn shelter design was the method of attachment of the blast door. Because of inadequate support for the blast door, the force of the blast at both 50 and 100 psi led to crumpling of the upper portion of the entrance shaft in the form of a compressed bellows.

Also of interest was that the twin blast valves functioned acceptably at 50 and 100 psi. Finally, there was no failure in the 0.109-in. cover or the 0.250-in. end plates. Air pressure buildups were 1.15 psi and 1.86 psi at 50 and 100 psi, respectively.

With the success of tests at Miser's Bluff, Event II-I, it became desirable to make further tests of multiple bursts using the full length (30 ft) of the shelter room to assure steel culvert performance independent of end phenomena. The nature of the Event II-II tests afforded the opportunity to determine the ability of the Donn shelters to withstand the longer duration load test which simulated the type of blast loading characteristic of larger yield nuclear weapons. The test consisted of a multiple detonation of 6 pods of 120 tons each of ANFO which exposed the shelter to overpressures, in quick succession, of 50, 60, 30, and 20 psi.

The only significant changes in the shelter tested at Event II-II, compared to the shelter of Event II-I, were:

1. Total length of the main shelter was 336 inches.

2. The formerly closed end was connected via the standard 30-in.-ID, 48-in.-long tunnel to a cellar.

3. The blast door was an elliptical sliding dome of 28-in.-diam., which was a combination blast door/valve.

4. Of special significance to future occupancy, a 160-lb dummy was placed in a double hammock suspended from the crown of the shelter with eyebolts. A 200-lb sandbag dummy was placed on 3/8-in. plywood supported on 2 X 4's on the shelter floor. Another 200 lb. sandbag dummy was placed on 4 inches of foam laid over 3/8-in. plywood supported by the shelter floor.

The Donn blast shelters survived the multiple blast effect without showing any signs of local buckling. Shelter diameter was changed by approximately 3%. The sliding blast door did not totally prevent pressure leakage. Pressure buildups were 2.8 psi in the main shelter, and 6.98 and 5.55 psi in the entrance and exit tunnels, respectively. The performance of the blast door may have been significantly affected by the collapse of the cellar. The conclusions were that the blast door should be redesigned.

Finally, the dummies sustained minimal stress and damage with movements of 2.69 in., 0.75 in., and 0.25 in. for the hammock dummy, the dummy on plywood, and the dummy on foam, respectively.

2.3.2 R. V. Kamath and M. D. Wright - RTI Report, Feasibility and Cost Analyses of Surge Period Shelter Program, 1980

The purpose of this report (Kamath and Wright, 1980) was to assess the feasibility and costs of providing all-effects shelters in risk areas for an in-place shelter plan as well as a population relocation plan. The major variables considered were time available, sheltered population, shelter design, and resource requirements and availability.

Construction costs, resource availability, and nationwide resource availability were assessed for six shelter designs - reinforced concrete rectangular shelter (500 and 1000 capacity), reinforced concrete arch shelter (500), steel arch shelter (500), steel dome corrugated culvert (20), and lumber shelter. For various surge periods, the capability of providing shelter spaces and minimum costs of providing protection to selected population groups were calculated. Critical resources that may limit shelter construction capability were identified.

However, the major items from the RTI study that will be considered in this review are the designs and updated cost estimates for several major types of blast shelters which have been considered major candidates for the large-scale blast shelter program historically. The first four shelters were of the more conventional type and each was designed to provide 10 ft^2 of floor space per occupant. Three modes of burial were considered: below grade, semiburied, or aboveground. The rectangular, reinforced-concrete arch, and steel arch shelters were all designed to protect against nuclear fallout and to withstand 30 psi free-field overpressure and associated thermal effects and initial nuclear radiation. It was stated that the above designs have been shown to withstand 50 psi incident pressure in actual blast (non-nuclear) tests, but no references were given.

The rectangular, reinforced-concrete shelter was based on a modularized design, with the 500-space shelter containing 20 modules, having dimensions of 80 ft long X 64 ft wide. Interior walls were 6 in. thick, exterior walls were 10 in. thick, and the roof was 18 in. thick. The reinforced concrete arch was a 4-in.-thick shell, 82 ft long with an

internal radius of 17.5 ft, and was set on arch footings. End walls were 10 in. thick with separate footings. The shell of the steel arch structure was 1/2-in.-thick steel plate. End walls were also 10-in.-thick concrete.

The steel dome shelter was based directly on the design extensively described and tested by the Donn Corporation (Donn, December 1978; March 1979). The RTI shelter is a resilient, high-strength, underground system designed to house up to 20 occupants for overpressures up to 50 psi. The RTI shelter design was based on burial of 39 inches to provide adequate protection from thermal effects and radiation. Entrances were constructed from vertical corrugated culvert section (about 30-in.-ID) connected to the ends of the main corrugated steel structure by short sections of 30-in.-ID culvert. The union between the horizontal, 30-in. connecting section and the main culvert (6.5-ft-ID) was accomplished by reducing the main structure cross section to 30-in.-ID with a conical attachment (sheet metal thickness was 0.109 in.). Blast protection was provided by high-strength, semielliptic, steel domes, equipped with integral fast-acting blast valves, placed directly over the top of the vertical entrance section. We believe that this design has certain shortcomings for blast pressures in excess of 10-20 psi. Among these are collapse of the vertical entrance section upon loading and insufficient arrangements for survival of ventilation shafts. Simple construction techniques for avoiding the weaknesses will be discussed in Section 4.1 on using corrugated culvert shelter for reduction of costs of shelter in general.

All data used in the RTI study to estimate costs for materials, labor, and labor productivity were obtained from two primary sources (R. S. Means Building Construction Cost Data and R. S. Means Mechanical and Electrical Cost Data). All costs were computed as national averages under normal economic conditions. These data can be adjusted to the costs in a particular state by using appropriate factors. Data for

determining the amount of reinforcement required for structural members of arch and rectangular shelters were obtained by the authors from the extensive IITRI work summarized in Civil Defense Shelter Options: Deliberate Shelters - Vol. II (IITRI, 1971). To provide an example of how RTI achieved their final cost figures, the shelter characteristics, material, labor cost factors and unit costs used to estimate the costs for constructing the 500-space rectangular reinforced concrete shelter are given in Table 2.13. A summary of the itemized shelter costs for burial condition 1 (below grade) for the 5 main shelters developed by RTI is given in Table 2.14.

Based on the costs for various other shelter design efforts, updated to 1982, these costs/space for rectangular and arch shelters appear unrealistically low. Items which appear to be underestimated are excavation and backfill costs and certain aspects of concrete work. The only study which produces cost figures anywhere in this ballpark are those of Havers and Lukes, for comparable level of comfort in the shelter (see Table 2.15). The basic shelter earthwork, entrance plus mechanical and electrical are included in the costs but comfortable habitability items, such as food, sanitation, water, hotel accommodations, and control package are not considered. It is interesting to note that the estimated 1982 costs of the Longinow and Stepanek shelter similar to the RTI rectangular structure are considerably higher.

There are several other pieces of information useful to reducing costs of blast shelters which may be gleaned from this report. First, the data were analyzed to determine what portion of the total structure cost could be attributed to mechanical and electrical costs. These percentages were necessary for updating cost data from various studies. A compromise figure for obtaining estimates was to add 25% of the cost of the basic structure (earthwork, entrance, main structure) to account for M&E. If there is a need for estimates of a more comfortable shelter, hotel accommodations, sanitation and control package can be estimated, we believe, relatively accurately by adding $50-$100/space to the other subtotals (See Section 2.4.1). There is so much variety in the types of food which can be supplied, ranging all the way from crackers, cheap canned goods, whole grain, or grain cereals to exotic freeze-dried foods,

TABLE 2.13. RTI 1980 COST FACTORS FOR BURIED 500-MAN RECTANGULAR CONCRETE SHELTER (KAMATH 1980)

Activity Description	Unit	Material/ Equipment Cost ($/Unit)	Labor Cost ($/Unit)	Total Cost ($/Unit)	Total Cost Incld. O&P ($/Unit)	Quantity Required (Units)	Time Reqd. (Crew Hrs.)	Material/ Equipment Cost ($)	Labor Cost ($)	Total Cost ($)	Total Cost Incld. O&P ($)
I. Earthwork											
Site Clearance	Acre	535.00E	755.00	1290.00	1650.00	0.5	5	268	378	646	825
Grub & Stump Removal	Acre	350.00E	140.00	490.00	580.00	0.5	2	175	70	245	290
Granular Fill	FT^2	10E	0.07	0.17	0.21	5,241.0	5	524	367	891	1,101
Excavation	YD^3	0.39E	0.20	0.59	0.71	4,028.0	43	1,571	806	2,377	2,860
Back Fill (Machine)	YD^3	0.75E	0.29	1.04	1.24	1,732.0	27	1,299	502	1,801	2,148
Back Fill (Hand)	YD^3	0	6.95	6.95	9.75	387.0	258	0	2,690	2,690	3,773
Tamping (Air)	YD^3	0.54E	2.55	3.09	4.17	387.0	19	209	987	1,196	1,614
II. Concrete and Reinforcements											
(1) Concrete											
Exterior Footing	YD^3	47.00M	33.00	80.00	97.00	21.2	2	996	699	1,695	2,055
Interior Footing	YD^3	47.00M	33.00	80.00	97.00	23.3	2	1,095	769	1,863	2,259
Exterior Walls	YD^3	66.00M	120.50	186.50	237.50	73.6	19	4,856	8,869	13,725	17,480
Interior Walls	YD^3	75.00M	185.50	261.50	331.50	62.8	25	4,773	11,649	16,422	20,818
Walls (Finishing)	FT^2	0.01E	0.19	0.20	0.27	12,544.0	136	125	2,383	2,509	3,387
Floor System (Casting)	YD^3	41.00M	28.00	69.00	84.00	55.9	4	2,292	1,565	3,857	4,696

(Continued)

TABLE 2.13. RTI 1980 COST FACTORS FOR 500-MAN BURIED RECTANGULAR CONCRETE SHELTER (KAMATH 1980) CONTINUED

Activity Description	Unit	Material/ Equipment Cost ($/Unit)	Labor Cost $/Unit)	Total Cost ($/Unit)	Cost Incld.O&P ($/Unit)	Quantity Required (Units)	Time Reqd. (Crew Hrs.)	Material/ Equipment Cost ($)	Labor Cost ($)	Total Cost ($)	Cost Includ. O&P ($)
Floor System (Finishing)	FT^2	0.00	0.17	0.17	0.22	5,241.0	58	0	891	891	1,153
Roof Slab (Casting)	FT^2	3.13M	0.65	3.78	4.35	5,241.0	18	16,404	3,407	19,811	22,798
Roof Slab (Lifting)	FT^2				1.29	5,241.0	2				6,761
(2) Reinforcement											
*Welded Wire Fabric	100 FT^2					45.8					
*Walls and Footings	TONS					15.9					
Roof Slab	TONS	345.00M	125.00	470.00	565.00	38.6	86	13,316	4,825	18,141	21,808
III. Water Proofing											
Vapor Barrier	100FT^2	1.50M	2.85	4.35	5.60	45.8	10	69	130	199	256
Exterior	100FT^2	2.30M	2.85	5.15	6.50	81.1	18	186	231	417	527
Drain Tile	FT	1.20M	0.81	2.01	2.45	308.0	6	370	250	619	755
Porous Fill	YD^3	5.25M	2.85	8.10	9.65	11.4	1	60	33	93	110

*Cost included in Section (1)

NOTE: See Tables 11, 12, and 13 of RTI Report for details of entranceways, electrical, and mechanical resource requirements.

TABLE 2.14. SUMMARY OF SHELTER COSTS FOR 5 BELOW GRADE RTI SHELTERS (KAMATH 1980)

SHELTER TYPE	REINFORCED CONCRETE			STEEL	
	RECTANGULAR		ARCH	ARCH	DOME
CAPACITY (PERSONS)	500	1000	500	500	20
1. Site Preparation ($)	891	1,246	1,068	1,068	249
2. Shelter					
Excavation ($)	2,377	4,247	4,158	4,158	101
Earthwork ($)	6,578	11,152	14,502	14,502	481
Structural ($)	85,876	162,009	66,307	102,675	3,178
Mechanical ($)	21,187	42,374	21,187	21,187	848
Electrical ($)	5,938	11,876	5,938	5,938	238
Shelter (Total) ($)	121,956	231,658	112,092	148,460	5,095
3. Entranceway ($)	5,173	10,038	5,019	5,019	*
4. Total Cost ($)	128,020	242,942	118,179	154,547	5,095
5. Total Cost Including Overhead and Profit ($)					
6. Gross Floor Area (S.F.)	5,120	10,240	4,644	4,644	120
7. Usuable Floor Area (S.F.)	4,872	9,704	4,636	4,636	120
8. Usable Area per Shelter Space (S. F./Shelter Space)	9.74	9.70	9.27	9.27	6.0
9. Cost (Including Overhead and Profit) per Square foot of usable area ($/S.F.)	32.25	30.73	33.42	39.94	51.13
10. Cost (Including Overhead and Profit) per Shelter Space ($/Shelter Space)	314.28	298.21	309.88	370.35	306.75
11. Costs/Space, 1982	392.95	373	387	462	383

*Included in shelter costs

Table 2.15 Comparison of Costs for Three Similar Design Studies

Study	Type of Shelter	Spaces	Level of Comfort	Cost/Space 1982 $
Havers & Lukes	Reinforced, rectangular, concrete cubicle, 50 psi	500	Common to all	342
RTI - Kamath & Wright	Reinforced, rectangular, concrete cubicle, 50 psi	500	"	392
Longinow & Stepanek	Reinforced, rectangular, concrete cubicle, 30 psi			
Option 6		500	"	817
Option 3		500	"	670
Option 2		500	"	543

Level of Comfort: Costs include structural, earthwork, mechanical and electrical. Not included were shock protection and habitability items (food, water, sanitation, cots, etc.)

that this cost factor probably should be estimated for such cases as austere, barely comfortable, very comfortable.

For example, corn meal can be bought in bulk for $0.06/lb (Jan., 1983). For this very austere diet, the cost amounts to about $5/month/person. Of course, this diet would have to be augmented with vitamins and minerals. We estimate the cost of permanent water storage to be about $1/gal.; or for 30 gal./person for a 1-month stay, this amounts to about $30/person for water. Reclaimed containers, or expedient measures (e.g., plastic bags in trash cans) can be much cheaper.

Two estimates of the costs of a corrugated steel culvert shelter are presented in the RTI report. In Table 2.16 are shown the cost estimates for a steel dome shelter with a capacity of 20. This summary was taken directly from Donn's brochure. We believe that several of the individual items are priced unreasonably low, and that other factors make this design unreasonable. The vulnerability of the entrance design to crushing at significant blast overpressures has been previously argued. The shelter has an internal diameter of 78 inches. Swiss experience has shown that to avoid claustrophobic effects on the occupants, the shelter should have an ID of about 8-9 ft. The cost for material appears far too low. Even if all the material costs could be allocated to the 30-ft main section, this allows for a cost of only $40/linear ft, omitting for the moment any consideration of connecting sections, entrance conduit, end pieces, or blast covers.

According to the original Donn document, the quoted price of $115/shelter (1978) was based on a 6-year, large-scale program for building 5.5 million shelters. Thus, the unrealistically low price may be at least partially explained by savings inherent in a very large program.

Perhaps with these considerations in mind, RTI arranged to obtain a separate estimate for the cost of end caps and obtained independent estimates of the other costs from standard reference texts. Details of those estimates for the 20-man culvert are given in Table 2.17.

TABLE 2.16 MATERIALS AND COSTS FOR STEEL DOME SHELTER (CAPACITY 20)

MATERIALS	POUNDS
SHELTER SHELL	2250
END CAPS	470
ACCESS TUNNELS	200
VERTICAL SHAFTS	570
ACCESSORIES	220
BLAST VALVES	150
TOTAL	3860

COSTS	DOLLARS
MATERIALS	$1110
LABOR, BURDEN G&A (EXCEPT CHARGES FOR PLANT & EQUIPMENT)	490
DISTRIBUTION	250
FIXED CHARGES: (PLANT & EQUIPMENT FULLY ABSORBED)	33
EXCAVATION	420
TOTAL COSTS	$2303

Table 2.17 Resource Requirements for Steel Culvert Shelter
RTI Report (1980 prices)

Activity Description	Burial Option	Material/ Equipment Cost ($)	Labor Cost ($)	Total Cost ($)	Total Cost Including O&P ($)
I. Earthwork					
Site Clearance	#1	75.00	105.00	180.00	231.00
Grub and Stump Removal	#1	49.00	20.00	69.00	82.00
Excavation	#1	67.00	34.00	101.00	121.00
Backfill (Machine)	#1	64.00	25.00	89.00	105.00
Backfill (Hand)	#1	0	271.00	271.00	380.00
Tamping (Air)	#1	21.00	100.00	121.00	163.00
II. Components					
Shell (1)	#1	1770.00	600.00	2370.00	2760.00
End Caps (2)	#1			300.00	350.00
Access Tunnell (2)	#1	70.00	24.00	94.00	109.00
Vertical Shafts (2)	#1	244.00	170.00	414.00	492.00
III. Total for 20 man shelter					4793.00
Cost/Space					239.65

NOTE: Burial Option #1 = grade level with berm

2.4 FRACTIONAL ALLOCATION OF SHELTER COSTS TO BASIC STRUCTURE AND HABITABILITY ITEMS

For several different design studies, we have calculated the relative percentages of total shelter costs which are contributed by the various structure and habitability items that constitute shelter construction and outfitting. These percentages were calculated for two different levels of habitability, austere and comfortable and for two valves of overhead, profit, and contingency (O, P, and C), 20% and 40%. For austere habitability, cost allocation was based on $30/space for habitability, representing a minimum for water and food for a 4-week stay. For austere mechanical and electrical equipment, we assumed a nominal $5/space, which should provide for minimal cooling by the simplest practical means, a Kearny Air Pump (Kearny, 1979). For comfortable habitability, cost allocation was based on $100/space for habitability, representing consideration of 30 gallons of water/space, food, sanitation facilities, and bunks. For comfortable mechanical and electrical equipment, a value of $50-$100/space was used -- a compromise number inasmuch as a value in excess of $300/space has been suggested for large shelters which must survive high blast pressures (>500 psi).

In general, at higher values of O, P, and C, the amount of shelter cost due to basic structural items (earthwork, entrance, structure) decreases. For a given value of O, P, and C, the percent contributed by basic structure depends on the habitability level. In general for 20-40% O, P, and C and the comfortable case, direct structure costs constitute about 50-55% of total costs with the remainder due to habitability, mechanical and electrical, contractor overhead, profit, and contingency, fees, etc. However, for the austere case, structure costs may constitute as much as 70% of the total shelter costs.

Another interesting trend is that the percentage of costs due to entranceways decreases as the number of spaces increases from the family to the 100- to 300-person category. After that, for a fixed pressure,

entrance costs stay more or less constant with shelter size. For a given shelter size, there are variations in cost allocation with pressure. Among the trends are: the percentage of costs due to habitability items decreases and the percentage of costs contributed by structural items increases as the design pressure level is increased. Although the cost/space for entrances increases with design pressure level, it increases slower than overall structural costs and thus the percentage of total cost allocated to entrances decreases as pressure increases.

In summary, for blast shelters designed for the low-pressure range (0-30 psi), a reasonable set of values for cost item percentage would be:

Austere case, 20% O,P,&C	Comfortable case, 20% O,P,&C
Structure - 60%	40-45%
Earthwork - 10%	5%
Entrance - 5-10%	5%
Habitability, Mechanical and Electrical - 5-7%	20-30%
Contractor's Overhead Profit and Contingency - 17%	17%

See Table 2.18 for details of some representative studies.

Table 2.18 Fractional Allocation of Shelter Costs to Basic Structure and Habitability Items

Cost Item	Percent Allocation: Austere OPC 40 - 20	Percent Allocation: Comfortable OPC 40 - 20
Design: Longinow & Stepanek, Option 3, Rectangular Reinforced Concrete, 500 spaces, 30 psi		
Earthwork and shelter structure	62 - 72	45 - 52
Entrance	4 - 4	3 - 3
Basic subtotal	66 - 76	48 - 55
Mechanical & electrical	1 - 1	12 - 15
Habitability	5 - 6	11 - 13
Overhead, profit, contingency (OPC)	28 - 17	28 - 17
Design: J. Havers, Rectangular Concrete Cubicle, 7-ft span, 100 spaces, 10 psi		
Structure	34 - 40	24 - 28
Earthwork	11 - 13	8 - 9
Entrance	18 - 20	12 - 14
Basic subtotal	63 - 73	44 - 51
Mechanical & electrical	1 - 2	11 - 13
Habitability	7 - 8	17 - 20
OPC	29 - 17	28 - 17
Design: Kamath & Wright (RTI), Rectangular Reinforced Concrete, 500 spaces, 30 psi		
Structure	53 - 62	37 - 43
Earthwork and site preparation	5 - 6	4 - 4
Excavation	2 - 2	2 - 2
Entrance	3 - 4	2 - 3
Basic subtotal	63 - 74	44 - 52
Mechanical & electrical	1 - 1	12 - 13
Habitability	7 - 9	17 - 20
OPC	29 - 17	29 - 17

Table 2.18 (continued)

Cost Item	Percent Allocation Austere OPC 40 - 20	Percent Allocation Comfortable OPC 40 - 20
Design: GATC, Steel Cylinder, 28-ft, 3-story, 500 spaces, 100 psi		
Earthwork	20 - 23	15 - 17
Shell structure	17 - 20	13 - 15
Hemispherical ends	8 - 9	6 - 7
Interior structure	10 - 12	8 - 9
Entrance	12 - 14	9 - 10
Basic subtotal	57 - 78	51 - 58
Mechanical & electrical	1 - 1	12 - 14
Habitability	4 - 5	10 - 11
OPC	29 - 17	29 - 17
Design: GATC, Steel Cylinder, 28-ft, 3-story, 500 spaces, 1000 psi		
Earthwork	8 - 9	7 - 8
Shell structure	37 - 43	33 - 38
Hemispherical ends	15 - 17	13 - 15
Interior structure	4 - 5	4 - 4
Entrance	6 - 7	5 - 6
Basic subtotal	70 - 81	62 - 71
Mechnical & electrical	0.2 - 0.3	6 - 7
Habitability	1.5 - 2.0	4 - 5
OPC	29 - 17	29 - 17

NOTE: Overhead, profit, and contingency were calculated by taking either 20 or 40% of the total of the preceding cost items.

In the work on design of entranceways conducted by Stevenson and Havers, the costs of the entrance was subdivided as follows:

55 to 60% of the costs for basic requirements for blast protection
22 to 27% of the costs for protection from ionizing radiation
15 to 20% of the costs for site preparation excavation slope stabilization, stairs and emergency exits.

2.5 SUMMARY AND REVIEW OF COMPARISON OF COSTS OF VARIOUS DESIGN STUDIES

A large number of literature studies containing diverse types of blast shelter designs with various cost factors has been presented in this review. Costs of the shelters in the year they were designed were extracted from the studies and updated for 1982, for what we believe is a reasonable level of construction and habitability. The revised costs for all the shelters of a particular study were plotted as functions of pressure and spaces to ascertain the most economical shelter. It is not the intention here to summarize observations about the design and costs of all of these shelters. Rather we will attempt to summarize in graphical form the costs of the most economical shelter designs from the various studies. Relevant comments concerning the most economical shelter designs as functions of space and overpressure, with particular focus on the corrugated culvert shelter, (described in section 4.1) are included. Six figures are presented in this summary.

In Figs. 2.2, 2.3 and 2.4, costs/space in 1982 dollars for the most economical shelters from each study are plotted as a function of overpressure in atmospheres (dynamic load) and psi static load. (1 atmosphere dynamic load is equivalent to a little less than 30 psi static load.) The figures differ because of the level of shock isolation and protection provided, that is, level 1, level 3 and none in Figs. 2.2, 2.3 and 2.4, respectively. Other basic structure costs and habitability are the same.

In Figs. 2.5, 2.6 and 2.7, cost/space for the most economical shelters from each study are plotted as a function of spaces per shelter. Shock protection levels 1, 3, and none are included in Figs. 2.5, 2.6 and 2.7.

The basic shelter factors included in the costs for these graphs are:

(1) earthwork (excavation and backfill);

(2) basic structure construction (concrete work, metal work, including materials and labor);

(3) entrance - materials and labor for excavation, blast protection, radiation shielding, stairs, etc.;

ORNL-DWG 83 9843R

Fig. 2.2 A COMPARISON OF THE MOST ECONOMICAL SHELTERS FROM VARIOUS DESIGN STUDIES

COST/SPACE vs OVERPRESSURE

BASIC FACTOR PLUS SHOCK PROTECTION LEVEL 1

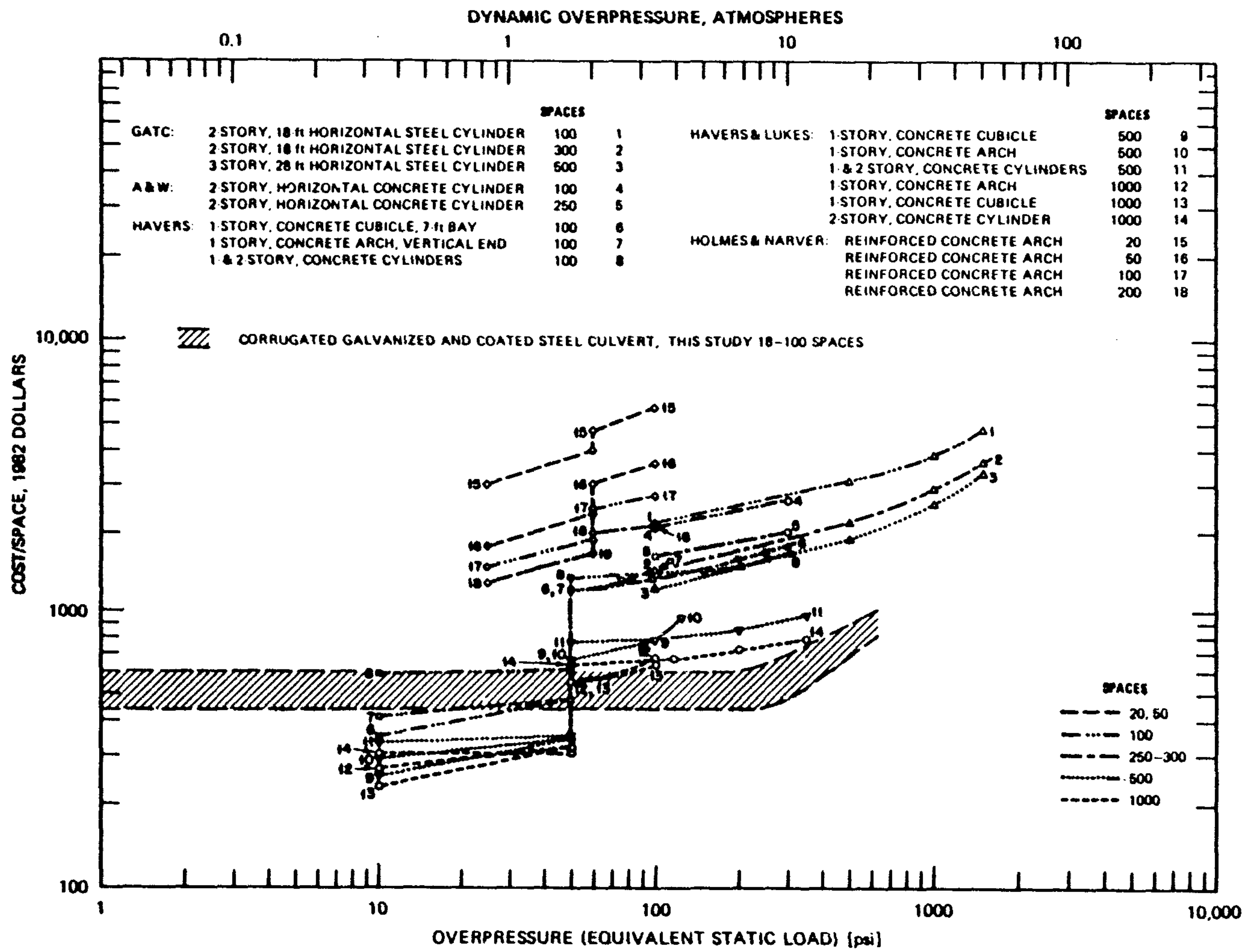


Fig. 2.3

C .NL-DWG 83 9846R

A COMPARISON OF THE MOST ECONOMICAL SHELTERS FROM VARIOUS DESIGN STUDIES

COST/SPACE vs OVERPRESSURE
BASIC FACTORS PLUS SHOCK PROTECTION LEVEL 3

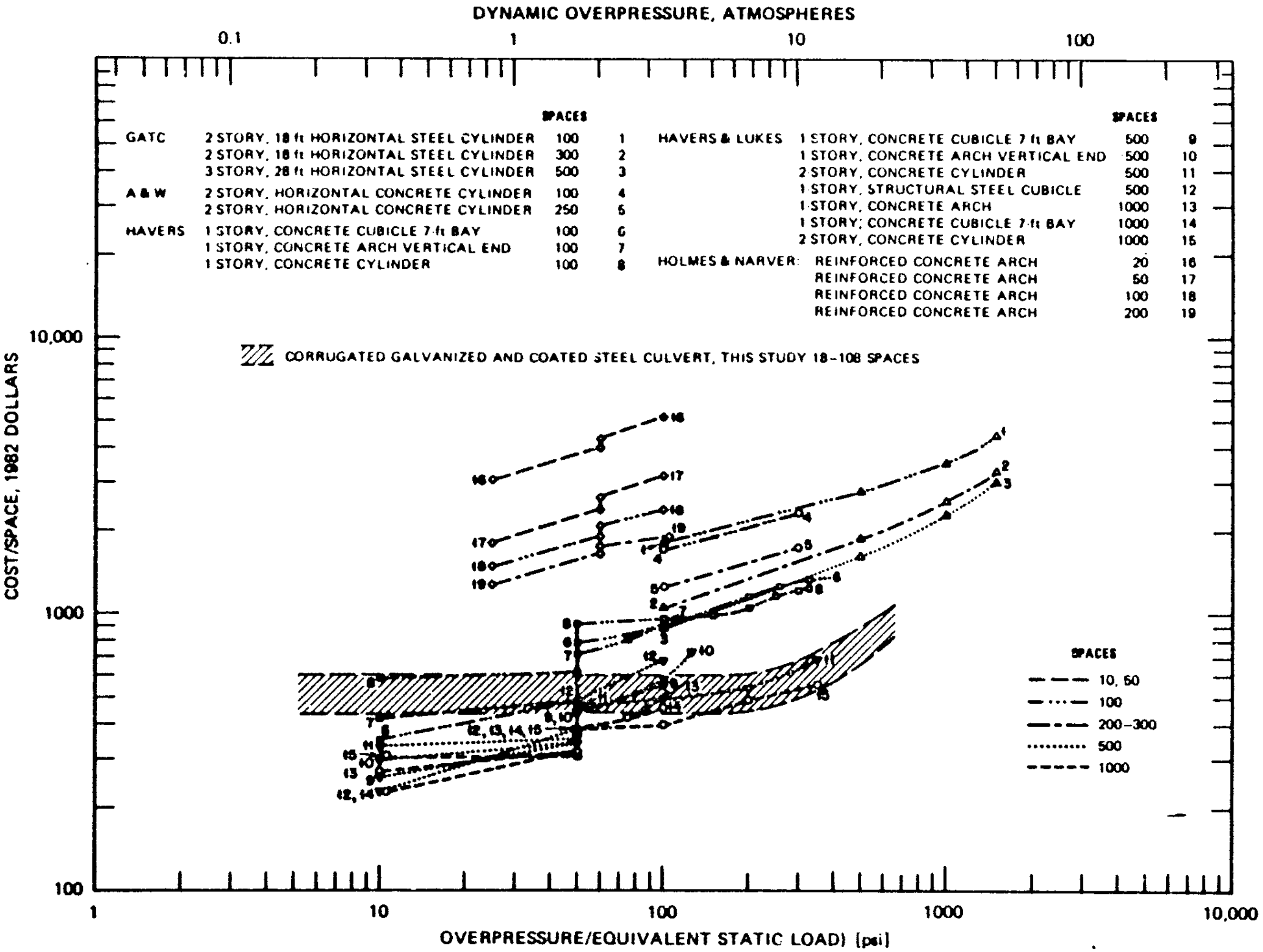
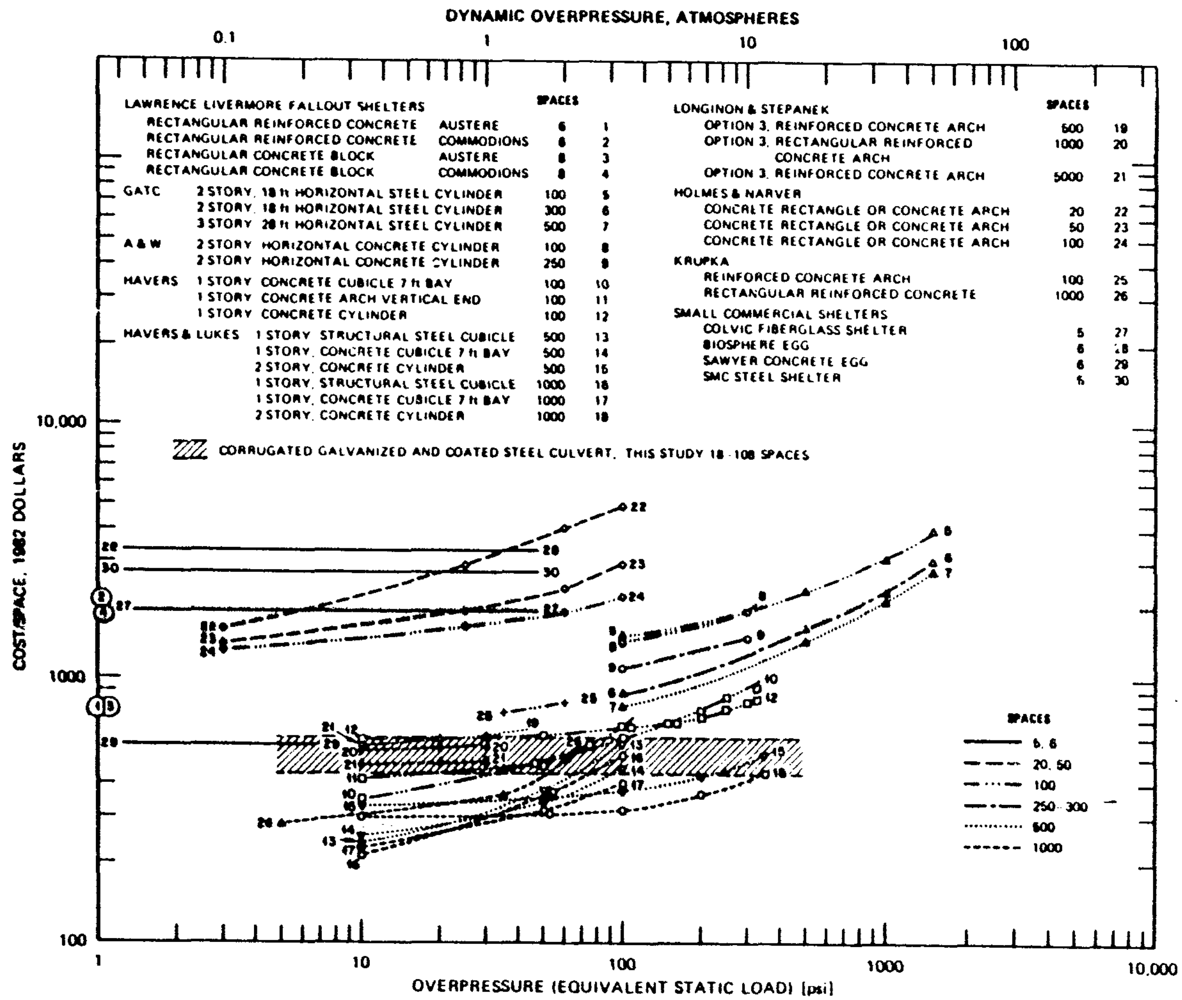


Fig. 2.4 A COMPARISON OF THE MOST ECONOMICAL SHELTERS FROM VARIOUS DESIGN STUDIES

COST/SPACE vs OVERPRESSURE
BASIC FACTORS
NO SHOCK ISOLATION

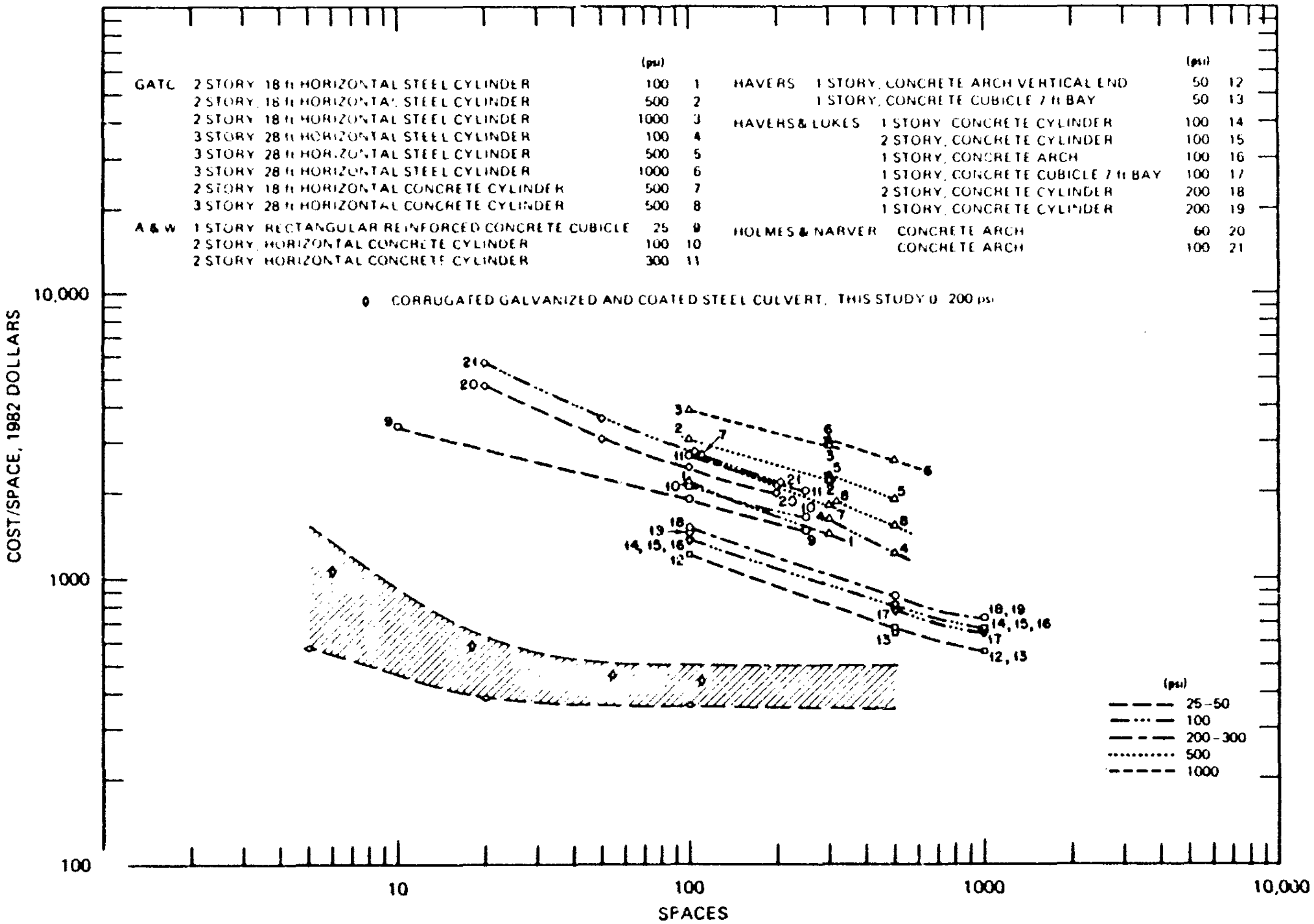
ORNL DWG 83 9847R



ORNL DWG 83-9844

Fig. 2.5 A COMPARISON OF THE MOST ECONOMICAL SHELTERS FROM VARIOUS DESIGN STUDIES

COST/SPACE vs SPACES (CONSTANT PRESSURE)
BASIC FACTORS PLUS SHOCK PROTECTION LEVEL 1

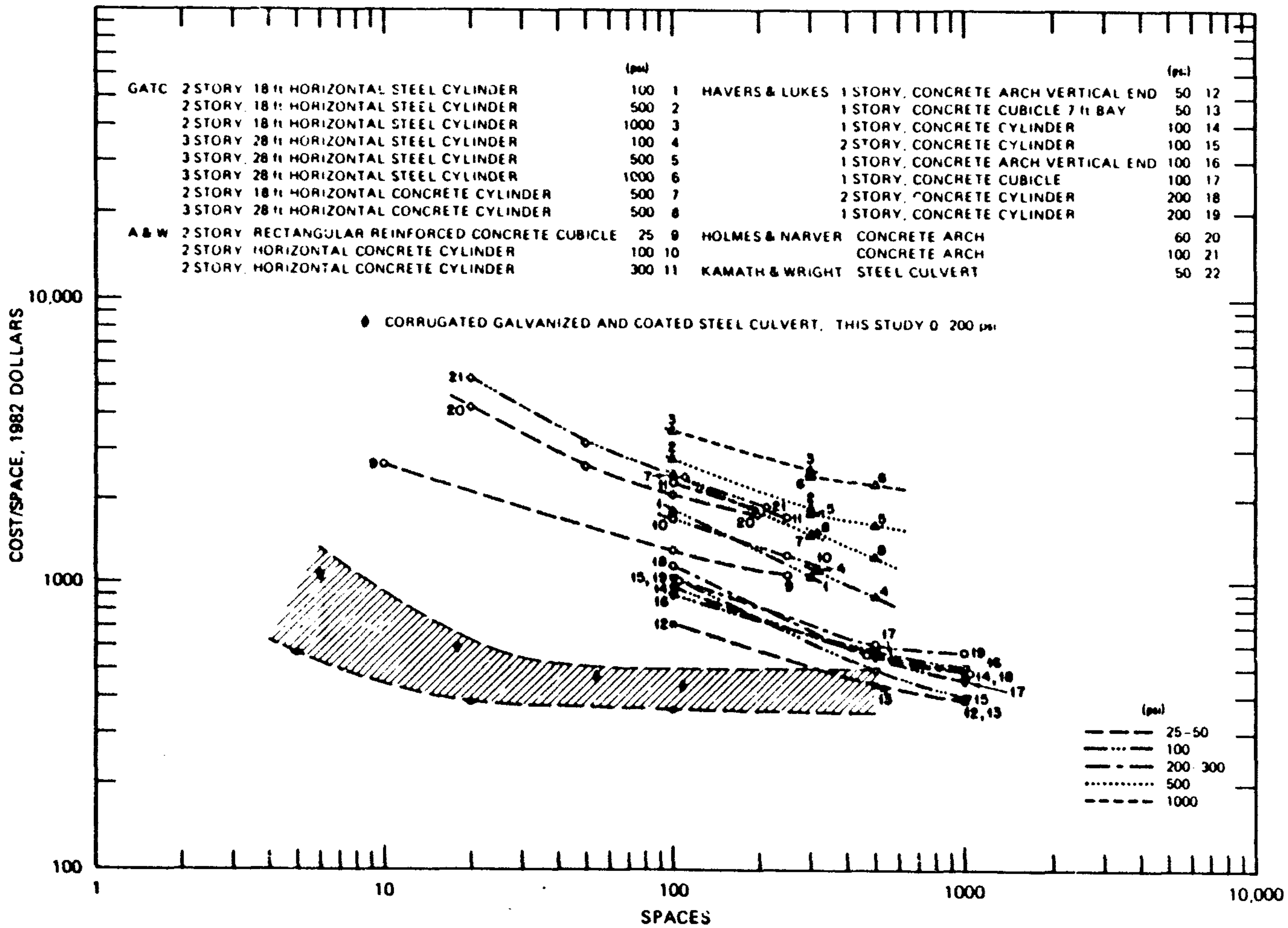


ORNL DWG 83 98-5

Fig. 2.6 A COMPARISON OF THE MOST ECONOMICAL SHELTERS FROM VARIOUS DESIGN STUDIES

COST/SPACE vs SPACES (CONSTANT PRESSURE)

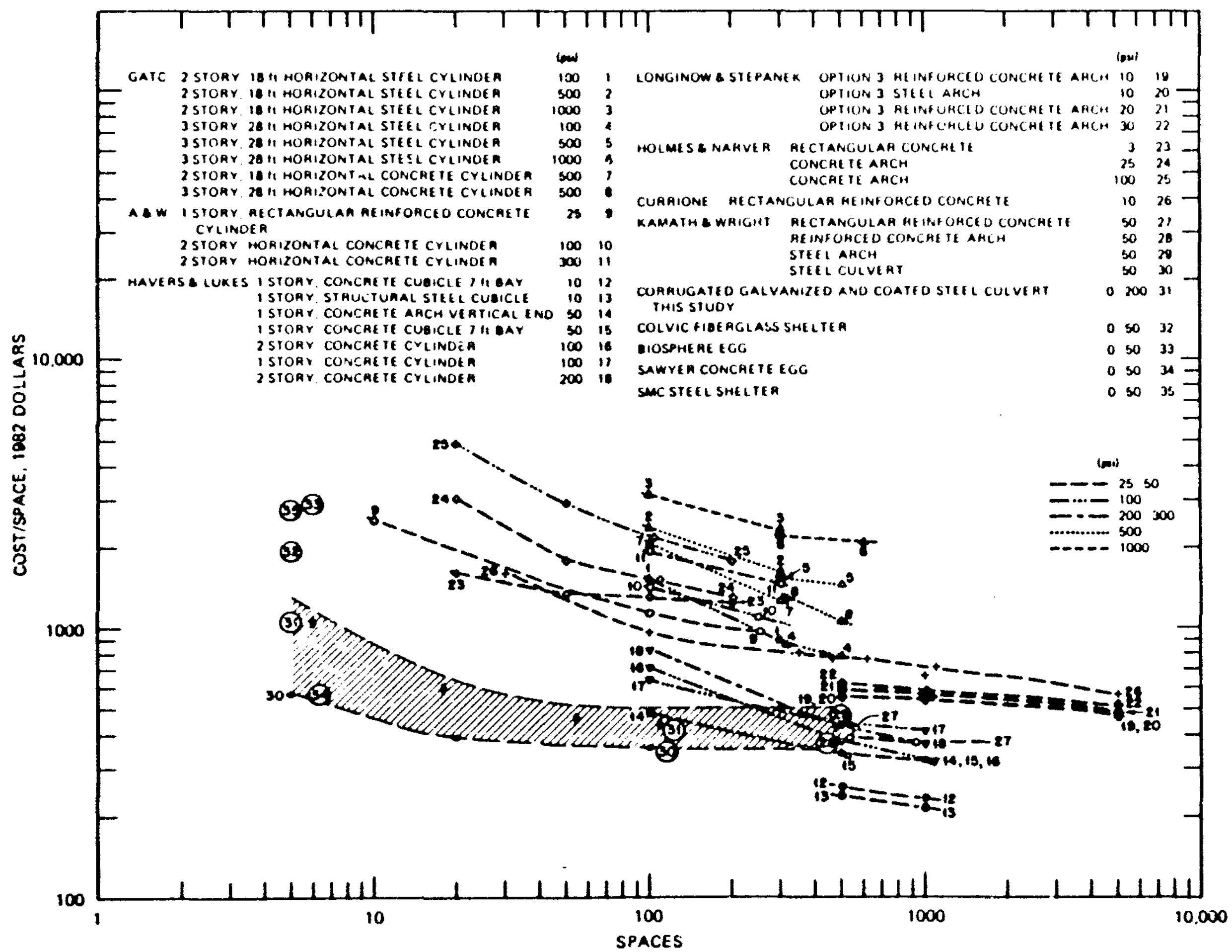
BASIC FACTORS PLUS SHOCK PROTECTION LEVEL 3



ORNL DWG 83-9848

Fig. 2.7 A COMPARISON OF THE MOST ECONOMICAL SHELTERS FROM VARIOUS DESIGN STUDIES

COST/SPACE vs SPACES (CONSTANT PRESSURE)
BASIC FACTORS
NO SHOCK INSULATION



(4) mechanical - primarily ventilation equipment, including air blowers, duct work, and external ventilation shafts, and necessary filters;

(5) electrical - lighting, outlets, mechanical wiring, back-up generator;

(6) contractor's overhead, profit, and contingencies taken at 20% for the prices calculated in Figs. 2.2 thru 2.7.

Costs are corrected to 1982 dollars by use of the Engineering News Record Index.

Key habitability items not included in the estimates of the costs in Figs. 2.2 thru 2.7 were: radiation monitoring and communications, food and water, bunks, and sanitation. For the interested reader, the prices in the summary figures can be adjusted to account for habitability by using the approximate percent allocations given in Section 2.4.

An initial inspection of the summary figures suggests several basic trends of blast shelter costs:

(1) For a specific study, cost/space decreases as the number of spaces increases. An approximate equation is

$$C_s = 1/s\ (C_e + C_L L)$$

for C_s = cost/space at one pressure.
C_e = cost/entrance
C_L = cost per length of main structure
S = no. of spaces
L = length of shelter for s spaces

(2) For a specific study, cost/space increases as the overpressure design level increases, represented by the equation

$$C_s = A + Bp^c$$

for C_s = cost/space for a shelter of fixed number of spaces.

(3) For a specific study, cost/space varies according to the type of architectural design.

2.5.1 Shock Protection Level 1 -- Cost/Space vs Pressure, Fig. 2.2

Costs for shock protection were included only for pressures equal to or greater than 50 psi. For the pressure range of 0-50 psi and 500-1000 spaces, the most economical shelters were the IITRI designs. For 500 spaces, the one- and two-story concrete cubicle and the one-story concrete arch were comparable in costs for low pressures (0-50 psi).

At higher pressures, the one-and two-story concrete cylinders of IITRI design were more economical than all shelters except perhaps the corrugated culvert.

2.5.2 Shock Protection Level 3 - Cost/Space vs Pressure, Fig. 2.3

In general, cost/space decreases for a given shelter configuration as the number of stories increases. For 1000 spaces, the one-story concrete cubicle and the one-story concrete arch were comparable in costs for low pressures (0-50 psi). At higher pressures, (100-350 psi), the two-story concrete cylinder was the most economical of the shelters reviewed in the literature. However, extrapolated values of cost/space for the corrugated steel culvert suggest that even at high levels of occupancy, for shock protection level 1 (which provides a high degree of protection from blast for occupants), the culvert would be the most economical type of shelter for pressures in the 50-200 psi range. At these pressures, further tests probably should be conducted with the culvert to ascertain the minimum type of shock protection equipment needed.

For the pressure range of 0-50 psi and 500 and 1000 spaces the most economical shelters were the IITRI designs. For 500 spaces, the one-story concrete cubicle and one-story concrete arch were comparable in costs at low pressures (0-50 psi). At higher pressures, the costs for two-story concrete cylinders were comparable with the corrugated culvert. For 100 spaces, the IITRI shelters were comparable in costs with the corrugated culvert only at pressures of 0-50 psi. For 1000 spaces, the one-story concrete cubicle and the one-story concrete arch were comparable in costs for low pressures (0-50 psi). At higher pressures, the two-story concrete cylinder was comparable in cost to the corrugated culvert.

2.5.3 No Shock Protection -- Cost/Space vs Pressure, Fig. 2.4

For the pressure range of 0-50 psi and 500 and 1000 spaces, the most economical shelters were the IITRI designs. For this pressure range and 100 spaces, the IITRI shelters were comparable in price to the corrugated culvert shelter.

For 100 spaces, the one-story concrete cubicle was the most economical of IITRI designs over most of the range 10-300 psi. For 500 spaces, the one-story structural steel cubicle and one-story concrete cubicle were the most economical at low pressures, but the two-story concrete cylinder and corrugated culvert shelter were the most economical at high pressures. For 1000 spaces, the one-story structural steel cubicle and the one-story concrete cubicle were the most economical at low pressures (0-50), but the two-story concrete cylinder was the most economical at pressures from 50-300 psi.

2.5.4 Shock Protection Level 1 -- Cost/Space vs Spaces, Fig. 2.5

The band representing the corrugated culvert shelter costs was constructed from estimates of the cost of the corrugated shelter made by both Kamath and Wright and by our calculations. The corrugated culvert shelter appears to be the most economical shelter for pressures of 50 psi or greater and spaces up to about 1000. As noted in the previous discussion of Fig. 2.2, however, some IITRI designs for 500 and 1000 spaces are comparable or less in price than the corrugated shelter for pressures of 0-50 psi. Our estimates of costs for the corrugated culvert shelter are higher than those of Kamath and Wright (updated to 1982) for several reasons:

(1) the culvert cross-section was larger, 9 ft vs 6-1/2 ft;

(2) culvert costs included bituminous coatings to increase service life;

(3) higher costs were estimated for entranceways and ventilation shafts to sustain higher pressures;

(4) more habitability items were included (cots, toilet, bungee cords); and

(5) higher costs were estimated for end closure.

The cost/space for the shelter for 6 men is higher than the cost/space for 18 men because two end pieces, two ventilation shafts and one entrance are needed for both cases. Some expense for the 6-man shelter could be saved by using a Kearny Air Pump and omitting the blower and generator.

2.5.5 Shock Protection Level 3 -- Cost/Space vs Spaces, Fig. 2.6

Again, the corrugated culvert shelter appears to be the most economical shelter for up to 1000 spaces, for pressures of 50 psi or greater (up to 200-300 psi). However, it should be recalled from Fig. 2.3 that for pressures of 0-50 psi and 500 and 1000 spaces, some IITRI shelters were predicted to be more economical than the culvert.

2.5.6 No Shock Protection -- Cost/Space vs Spaces, Fig. 2.7

Again, for pressures of 50 psi or greater, the corrugated culvert shelter is the most economical shelter up to about 500 spaces where some IITRI designs became competitive. These IITRI structures include the one-story concrete arch, the one-story concrete cubicle and the one- and two-story concrete cylinders. For 10 psi and 100 spaces the one-story concrete cubicle and one-story structural steel cubicle are more economical than the corrugated culvert. Also included in this figure are estimated cost/space for several widely advertised, commercially available, small family-size shelters and one personally designed shelter (H. A. Sawyer). The Sawyer shelter is the only one that is comparable in price to the corrugated culvert. Also of interest are the costs of Longinow and Stepanek shelters for 10, 20, and 30 psi and 500 to 5000 spaces and the costs of a recent study, that of Kamath and Wright. It appears that the costs/space for Longinow and Stepanek studies are only comparable with the corrugated culvert at very high levels of occupancy. The costs/space for the RTI study appear to be comparable with the costs of the corrugated culvert at 500 spaces or greater.

3. COST REDUCTION METHODS

A blast shelter is a system designed to protect occupants from the effects of weapons and to keep them alive and healtny for some significant time afterward. As was done in the first part of this report, costs can be broken down into the structural components, which include the structure itself, entrances, ventilation intakes and blast valves, and habitability items. The last category includes air handling and moving equipment, water storage, sanitation, food, light, and sleeping provisions.

The extremely austere habitability packages which will keep people alive (though not comfortable) for two weeks can be assembled for a relatively few dollars per occupant from commercially available materials. At the opposite extreme, hotel facilities for important command and control centers can cost upwards of a few hundred dollars per person. Reducing the cost of habitability items requires making a policy decision on how austere a shelter environment will permit the occupants to carry out whatever tasks are necessary and will make the plans acceptable to the people who must participate in them and who must approve and fund them.

In most shelter designs, the structure of the shelter envelope is the major cost, especially for large shelters with long allowable times for entry. Small shelters or shelters which must be filled quickly may require a larger fraction of their cost to be invested in entranceways. Ventilation intakes, including blast valves, are a significant expense for high-overpressure shelters and especially shelters which must function in a severe rubble environment.

Most shelters, especially those of reinforced concrete construction, are designed to resist the entire load produced by the weapon overpressure with little, if any, credit taken for pressure attenuation due to the earth. Most shelters have been designed to survive in essentially liquid soils.

We be' the major opportunities for cost reduction lie within the cost . cructure. And it is by exploiting the strength of the

earth that these reductions can be achieved, at least for smaller shelters.

3.1 DUAL USE

There are two ways to reduce the apparent cost of any commodity, service, or capital item: one is to make it or do it cheaper, the other is to make some other person or activity pay for it. This is sometimes known to economists as cost displacement. It is an old concept in civil defense, with many studies of slightly modifying belowground space to function as blast and/or fallout shelter.

It is very inexpensive to design above- or belowground masonry structures to provide very good fallout protection. It is much more difficult and expensive to modify even the belowground portion of structures to resist blast, especially to the three-atmosphere level of interest for sheltering critical workers.

3.1.1 Parking Garages

Parking garages are an obvious example of a structure which is adaptable to dual use. They are useful almost anywhere there is human activity. When built belowground, their robust structure is easily adapted to blast resistance. The expensive consideration is usually the closures for the vehicle entrances. The chief drawback is that their peacetime use is economically competitive only in very high population density areas, such as downtown cities, usually with an associated rubble problem. In suburban or industrial park areas, land is sufficiently inexpensive that the economical solution to parking is the ubiquitous, blacktopped acres of parking area.

3.1.2 Earth-Sheltered Residences

Recent years have seen the development of residences and small commercial structures surrounded on multiple sides and the roof with earth, principally to achieve energy conservation. This type of structure shows promising adaptability to the lower range of overpressures and is discussed at length in the companion report to this, ORNL 5957.

3.1.3 Caves, Mines and Tunnels

Caves, mines, and tunnels inherently have very high fallout protection factors. Unfortunately, they are usually not available in areas where there is a blast threat. Those that are available -- for example, the limestone mines under Kansas City -- may require roof support if they are to be used where there are expected high levels of blast overpressure and its associated ground motion. Caves and mines often have very limited access openings, designed, in the case of mines, for small numbers of people. The use of these facilities eliminates the cost of the shelter structure, but not the requirement for habitability packages. Ventilation, in particular, may be somewhat more expensive than for smaller shelters due to the long runs of intake and exhaust duct which may be required.

All densely-populated areas have a continuing requirement for concrete aggregate. In those areas underlain with competent rock, a policy of incentives for mining the rock in configurations subsequently adaptable to shelter can produce very hard shelter at acceptable cost. Some subsidy would be required, since underground mining is always much more expensive than the usual openpit mines used to produce concrete aggregate. New York City and Kansas City are examples of areas underlain by competent rock.

3.1.4 Expedient Upgrading of Existing Below-Grade Space

Existing belowground space may be upgraded in a crisis against moderate overpressure blast threat. The requirement is that the floor covering the shelter space be concrete and at or below ground level to avoid dynamic pressure from wind drag.

Most commercial underground space has relatively long-span concrete floors over it. Minimum bay dimensions are rarely under twelve to sixteen feet. The floor is designed with adequate thickness and steel to support useful loads, rarely under 150 pounds/sq ft, without noticeable deflection. The ultimate strength of these floors is usually two or three times the design load. Bending moment in these members is inversely proportional to the square of the span. By breaking the span with improvised or preplanned columns and lintels,

loadbearing capacity of the floor can be greatly increased. By reducing a 12-ft span to 4 ft with two additional rows of columns in a 12-ft bay, the theoretical bending loads supported by a floor are increased by a factor of nine. For real poured-in-place concrete floors, this would result in an overpressure capability close to two atmospheres (30 psi). Of course, adequate attention must be given to other modes of failure of the floor under loads such as shear or punching. These can be handled with appropriate lintels or capitals on the columns. These techniques were demonstrated in the MILL RACE event (Tansley, 1982).

Most below-grade commercial space has sizeable openings which must be closed for blast protection. As a minimum, there will be open stairwells and possibly elevator shafts. There may also be large vehicle entrances or windows on exposed vertical walls. Custom designed concrete blocks or beams cast before the crisis and stacked in a convenient place as part of the crisis preparation can be an economical solution to closing large apertures.

Earth arching can be employed, especially for vehicle entrances if they have sufficiently strong frames. A yielding metal door covered with more than half a span of sand, gravel, or crushed rock will provide a secure closure.

In one- or two-story buildings, additional earth cover on the floor would be required for radiation protection, especially initial nuclear radiation at overpressures as low as two atmospheres. Getchell and Kiger (Getchell, 1980 and 1981), of the Army Corps of Engineers Waterways Experiment Station, have demonstrated significant improvement in the hardness of concrete panels with sand coverage as low as 1/5 of the span. Sand coverage equal to half the span, when adequately compacted, is capable of transferring virtually the entire load from the span to sufficiently rigid end supports.

It should be emphasized that it is difficult with the techniques described here to get hardnesses greater than two atmospheres. For critical workers, a minimum of three atmospheres is highly desirable.

All the techniques described are useful in one- to two-story buildings. In buildings higher than four stories, rubble complicates the problem of survival in basement shelter (Bernard, 1983). Depending on building construction and contents, fire may present an additional survival problem to basement shelter occupants. For these reasons, combination escape/ventilation tunnels should be provided if rubble and fire are potential problems.

3.2 SINGLE-PURPOSE SHELTER

3.2.1 Basement Shelter in New Buildings

Incorporating a blast shelter in one corner of a concrete basement is a very economical way to achieve a structure with the necessary strength for a blast shelter. If the walls of the shelter coincide with bearing walls required by the building structure and the roof with an existing floor, incremental cost of the shelter structure is very low (almost negligible) in the cost of the building. This has been the general approach for civilian shelters in Switzerland, which requires by law the construction of one- to three-atmosphere shelters for occupants in all new buildings.

The shelters still require doorways, ventilation intakes, and escape tunnels, which add significantly to the structure. In the case of the Swiss, high-quality ventilating equipment is required, as well as other quite adequate habitability items. It is probable that the shelter access and intakes and habitability equipment account for most of the $700-$1000/space cost reported for the Swiss system.

The large structural savings possible with new construction are almost nonexistent if this type of shelter is to be retrofitted into an existing basement or building.

One of the major problems with basement shelters is the hazard from fire in the structure above. While this would be a strong function of the use and contents of the structure, experience with holocausts in so-called "fireproof" hotels tends to make one somewhat apprehensive about the survivability in this structure.

It is possible to design a shelter in a building basement that can tolerate the complete combustion of the building above it. It requires walls of adequate thickness exposed to the interior of the building and very careful attention to ventilation intakes some distance from the building. In addition, the blowers or air pumps should be arranged to pressurize the shelter with respect to the building, to avoid infiltration of carbon monoxide.

In buildings of more than three or four stories, rubble can become a severe problem. This was demonstrated recently by Bernard and Wilton (Bernard, 1983) in their study of the controlled demolition of high-rise buildings. Escape tunnels on at least two sides of the building going out some distance would be required. In central business districts where city blocks are filled solidly with buildings eight stories and up, there may be insufficient area around the blocks to permit escape with any degree of reliability. The only solution in which one can have confidence is then a tunnel network interconnecting all the shelters in the area with redundant exits in the open areas that are available. Studies of such systems usually arrive at the conclusion that the connecting tunnels offer the potential of enough shelter space in themselves. This was the case of the tunnel grid system suggested by Howard Harrenstein at the University of Arizona and studied at the Oak Ridge National Laboratory in the mid-sixties (Harrenstein, 1964; Robbins, 1965).

3.2.2 Earth Arching

Most drained soils, when subjected to a compressive load, develop shear strength. This strength is maximum for consolidated granular soils such as sand, gravel, and crushed rock. It is much lower to non-existent in soft clay, peat, and soils below the water table.

If a structure which can yield slightly without failing is buried in a granular soil and then subjected to surface pressure, the shear strength developed in the soil will transmit the pressure around the structure. In the extreme case, the structure need assume almost none

of the applied load, but simply keep the soil adjacent to it from falling into the interior.

This phenomenon is called earth arching. The depth of cover required to fully develop it may be estimated from a simple model developed by Funston, Woo, and York of the Boeing Company (Funston 1978). In this model, it is assumed that the failure angle of the soil is equal to the angle of internal friction of the soil, which is theoretically true for cohesionless soils. For full arching, soil failure planes tangent to the shelter must intersect below the surface of the soil compacted by the blast. Table 3.1 gives depths of cover required for full soil arching in terms of the width or diameter of the shape for cohesionless soils of internal angles of 30° and 45°. Thirty degrees is representative of a sandy clay, and 45° is representative of a clean, sharp, sandy soil.

Table 3.1 Required Earth Cover for Full Soil Arching

Angle of	Depth of Cover/Span for	
Internal Friction	Long Rectangle	Horizontal Cylinder
30°	.866	.500
45°	.500	.207

From the table, it is apparent where the rule-of-thumb originated that earth arching requires a depth of cover equal to half the span. This is the case for sandy soils on a rectangular structure and sandy clay soils on a cylindrical structure.

Shelters designed for two or three atmospheres overpressure would require four or five feet of cover to protect the occupants against nuclear radiation and, correspondingly more at higher overpressures. For many useful sizes of shelter, the protection against initial nuclear radiation provides adequate cover to develop earth arching.

In the U.S. Nuclear Weapons Test series between 1951 and 1958, there were several tests of corrugated metal shelters of various designs protected to varying degrees with earth cover (Beck 1969). The results are summarized in Table 3.2. The shelters were all constructed of Armco corrugated steel structural plate, which has a 2-in.-deep corrugation on 6-in. pitch. Gauges ran from one to twelve, with ten being the most common. Shapes ran from 7-ft-diameter circles to 38-ft-diameter arches, and included some 5-ft x 8-ft cattle passes.

The results are entirely consistent with the simple model of earth arching mentioned just previously. All the structures that survived had adequate depths of cover of reasonably good soil. From reading the reports, it appears that the experimenters were aware of the qualitative phenomenon of earth arching but did not have quantitative understanding of it. This is indicated by their attempt to strengthen the structure by using heavier-gauge metal rather than improving the quality of the soil or the depth of cover, as they did with the 38-ft arch on the KOA shot in 1958. The 7-ft-diameter circular shelters in the Smokey shot in 1957 with 10 ft of earth cover were grossly overdesigned from the structural standpoint. The 10 ft of cover was required partly by initial nuclear radiation.

The 25-ft arches tested in the Priscilla shot were among the most interesting, since they survived 60 and 100 psi. These are interesting because the experimenter went to the additional trouble to import a high-quality gravel backfill, in addition to burying them flush with original grade. Some slippage of the bolted seams suggests that the structure was stressed to a significant fraction of its ultimate

Table 3.2 Nuclear Blast Tests of Corrugated Metal* Shelters
(*Armco corrugated steel structural plate)

Date	Operation	Shot	Shape	Diameter ft.	Thickness Gauge	Grade to Crown Distance ft.	Crown Cover ft.	Yield KT	P psi	Comments	Page # in CEX 68.3
28/10/51	Buster	Baker	Arch	~7	12	-3	3	3.5	8	Survived 3 shots; open shelter	1
30/10/51		Charlie						14.0	15		
1/11/51		Dog						21.0	15		
28/10/51	Buster	Baker	Circular	7'6"	10	-1'8"	3'8"	3.5	9	Total 1.5" deflection in 4 shots	8
30/10/51		Charlie						14.0	24		
1/11/51		Dog						21.0	25		
5/11/51		Easy						31.0	6		
19/5/53	Upshot - Knothole	UK 9	Arch	25	10	+12-1/2 (surf. berm)	3	32.0	10.8	Structure OK; door support failed	47
20/5/53		UK 10						15.0	8.1		
15/4/55	Teapot	12-Met	Arch	25	8	+12-1/2 (surf. berm)	3	22.0	30 static 160 dyn.	Collapsed from windward side	91
31/8/57	Plumbbob	Smokey	Circular	7	10	-10	10	44.0	245	No damage. 2.5' subsidence; Soil ρ = 113; Tan α = 1.42; α = 54.8°	304
31/8/57	Plumbbob	Smokey	Circular	7	10	-10	10	44.0	190	No damage. Tan α = .875; α = 41°	304
24/6/57	Plumbbob	Priscilla	Cattle Pass	5'6"x7'8"	10	-7-1/2	7-1/2	37.0	149	No damage	143
	Plumbbob	Priscilla	Cattle Pass	5'6"x7'8"	10	-5	5	37.0	126	No damage	
		Priscilla	Circular	8	10	-7-1/2	7-1/2	37.0	126	No damage	
		Priscilla	Arch	25	10	0	5' gravel	37.0	60	Survived. Seam movement	153
		Priscilla	Ribbed Arch	25	10	0	5' gravel	37.0	100	Survived. Seam movement	153
5/5/58	Hardtack	Cactus	Arch	25	10	+12-1/2	5	18.0	85	Collapse Downwind	327
12/5/58	Hardtack	Koa	Arch	25	10	+12-1/2	5	1310	78	Complete collapse with joint failures; Low "density" coral sand berms	327
		Koa	Arch	38	1	+19	5	1310	83		
		Koa	Arch	25	10	+12-1/2 (all surf. berm)	5	1310	180		

strength. If one makes that assumption, and given the 5 ft of cover on a 25-ft arch, one calculates that the lower limit of the angle of internal friction of the gravel was about 44°, a reasonable number.

Identical structures tested in the same pressure range in the Koa (1310 KT) and Cactus (18 KT) shots at Eniwetok in the following year failed catastrophically. This was due not to the shot duration, but to the fact that the cover was a surface berm subject to dynamic loading; and, more importantly, that the backfill was an extremely poor-quality coral sand containing large amounts of small sea shells and very difficult to compact.

The only cases of completely below grade structures protected by earth arching which were tested to destruction were carried out by Kiger and Getchell (Kiger, 1980-1982) of the Army Engineers' Waterways Experiment Station in Vicksburg, Mississippi from 1978 to 1981. The results are summarized in Table 3.3. These tests, which may be the most carefully instrumented tests of earth arching done so far, were carried out with shallow-buried, flat-roofed, reinforced concrete structures. The structures, which were intended to be 1/4-scale models of reinforced concrete bunkers, were 4 ft X 4 ft X 16 ft in inside dimensions. Wall thicknesses were 1/10 the minimum spans, and contained 1% tensile steel and 1-1/2% shear steel. The specimens were subjected to blast pressures of approximately 2000 to 8000 psi, using the Foam HEST technique intended to simulate the effects of kiloton-range nuclear weapons. Depths of burial equal to 1/2 the span in sand and clay, and 1/5 of the span in sand, were tested. In addition, 1/8-scale models with the same cover were hydrostatically tested to destruction in a test chamber.

All structures exhibited substantial enhancement of their strength due to earth arching, even with covers as low as 1/5 the span or with the use of clay as a backfill. The statically-tested structures had a design strength on the order of 160 psi and exhibited static strengths

Table 3.3 Summary of Earth Arching Experiments by Kiger and Getchell

Test	Scale	Span	Fill	Scale Yield KT	Calculated Strength, psi	Span/Depth	p psi	Comments
Static 1	1/4	1/2	sand			10	620	Ultimate load
Foam HEST 1	1/4	1/2	sand	12.8		10	1900	Light damage
Foam HEST 2	1/4	1/2	sand	256.0		10	9000	Roof collapse; punching
Static 4	1/8	1/5	sand		164	10	358	1" roof deflection; ultimate
Foam HEST 4	1/4	1/5	sand	12.8	164	10	1900	Severe damage; 1' deflection; near collapse
Static 5	1/8	1/5	sand		1286	4 (1.5% steel)	1265	Ultimate
Foam HEST 5	1/4	1/5	sand	45-500	1286	4	8000-17,000	No arching; moderate damage
Static 3	1/8	1/2	clay		107 simple 156 in plane comp.	10	240	Maximum load
Foam HEST 3	1/4	1/2	clay	6-70		10	1700-2900	Moderate damage; 6" deflection
Foam HEST 6	1/4	1/2	clay	45-134		10	6600-9200	Complete roof collapse
Foam HEST 7 Multiple Bay	1/4	1/5	sand	18-150		10	1700-	Complete roof collapse

of 620 psi when covered with a 1/2-span depth of sand, 350 psi with a 1/5-span depth of sand, and 240 psi when covered with a 1/2-span depth of sandy clay.

Under very short-duration overpressures simulating pressures from tactical nuclear weapons, the strength of the structures approached 2000 psi. The dynamics of the process are not well understood.

3.2.2.1 Application of Earth Arching

A major component of the cost of blast shelter is the load-bearing structure in traditional reinforced concrete designs. Earth arching offers the prospect of transferring most of the load on that structure to the surrounding soil, with the possibility of significant reductions in cost. All that is required is a structure with the strength to resist the dead weight of the soil and the backfilling operation, but with less stiffness than the compacted soil. If buried to a sufficient depth in a drained soil with a significant angle of internal friction, under blast loading the soil will assume most of the load. The importance of compliance or yielding ability in the structure must be emphasized. Structures which are stiffer than the soil (for example, concrete domes) can experience stresses greater than those imposed on the soil by the blast load. The soil will transfer load to the structure.

The most economical permanent structure that we have been able to find that satisfies the requirements for earth-arching is one made of corrugated metal culvert. Shelters constructed of wood, especially when constructed of indigenous free materials, such as small trees and do-it-yourself labor, are of course much more economical. However, they cannot be considered permanent shelters. Wood in contact with the soil in warm climates with significant rainfall will have a service life measured in a very few years, if untreated, and cannot be depended on for more than 20 years, no matter what the treatment.

Corrugated culvert has demonstrated capability for very useful service life in soil in all parts of the country. It is available in all parts of the country and is manufactured in large quantities. It is generally less expensive to transport from the manufacturer to the installation site than a corresponding prefabricated reinforced concrete structure. Its relatively low weight provides savings in handling and installation costs, which offset its somewhat higher material costs compared to reinforced concrete. As indicated in the previous section on cost analysis, for applications against any significant blast pressure in smaller shelter sizes, corrugated culvert has a cost advantage over all other methods of construction for permanent shelter. Tests of the Donn Corporation corrugated metal shelter in the MISERS BLUFF event in 1978 demonstrated the capability of this structure to resist overpressures above 100 psi from 120-ton explosions. There appears to be a growing consensus that corrugated metal culvert is the material of choice for blast shelters when designing for:

(1) permanent shelter,

(2) under 100-occupant capacity,

(3) above the water table,

(4) depth of cover equal to at least 1/2 the diameter of the shelter,

(5) soil with a significant angle of internal friction (at least 30°).

3.2.2.2 Other Yielding Structures

Reinforced concrete structures can exploit earth arching if they are designed with the necessary compliance or ductility. This can be done by appropriate design of the reinforcing steel in the structure and by designing the structure to resist the earth overburden and not the blast pressure. (Of course, the entrances have to be designed for the blast pressure.)

Earth arching can be exploited to protect inherently rigid structures by placing a compressible or yielding material between the structure and the earth. This technique is sometimes called "compressible backfill" or "backpacking". The work of Kiger and Getchell (op. cit.) has demonstrated that very little yielding is required to develop earth arching. Experiments by the Boeing Corporation demonstrated the feasibility of protecting very rigid structures, such as large machine tools, with compressible backfill in the form of bags of aluminum turnings and earth cover (Funston, 1978).

Harrenstein (September, 1964) suggested yielding structures with a great deal of ductility to develop membrane stresses in panels as a way of reducing cost, compared to building the panels to function as two-way slabs.

3.2.2.3 Sand Closure

The possibility exists of filling properly-designed entranceways with sand as an inexpensive substitute for conventional blast doors, for entrances which are not needed or are needed only infrequently under crisis conditions. An example might be a vehicle entrance to an underground garage which has been upgraded to a blast shelter during a crisis. The rest of the structure might be designed with enough cover to function as blast shelter against useful overpressures at little additional cost. However, conventionally-designed blast doors for large entrances are very expensive.

A conventional rolling steel door may function as an adequate closure if it is covered on the outside with a quantity of sand covering the door with a thickness equal to the minimum span of the door. However, the frame around the door must be designed to take the load on this area and provision must be made for adequate bearing surfaces to support the compacted sand. These can be surfaces parallel to the plane of the door which are wide enough to provide a shoulder to bear

against the sand plug. Alternatively, they could be surfaces parallel to the direction of travel through the door -- for example, a driveway, which had been roughened or serrated to provide a shear bond to the sand plug.

For maximum convenience, a sand storage area above the entrance should be provided to permit filling the entrance by gravity. A pneumatic conveying system can be provided to empty the entrance when the danger of blast is past.

3.2.2.4 Membrane Door

As has been noted frequently, costs of a door are often a major expense in shelters, especially those for smaller numbers of people. These costs are minimized if the door can be made as light as possible, commensurate with the design blast pressure. In addition to the materials in the door, savings also can be significant in the expense of the hinge-opening mechanisms, counterweights (if any), etc. The minimum-weight-door will result from using a spherical membrane to resist the pressure and a circular ring beam to support the edges of the membrane. With proper design and mass production, this approach should result in the lowest-cost door. A concept employing these principles is described later in this report (Sect. 4.1.2) under the description of the corrugated metal shelter concept.

3.3 INSTITUTIONAL FACTORS

Cost estimates of carefully-engineered designs give numbers which can be achieved under ideal conditions. Less-than-ideal conditions are usually allowed for in an item called "contingency," which encompasses such things as unfavorable weather or supply interruption. Greater non-idealities can occur due to such things as labor work rules, zoning laws, and building codes. These must be given careful consideration in

efforts to reduce cost of the design. Often, large amounts of money can be saved by using a slightly more expensive material or construction method which reduces the number of crafts needed to complete the job. Careful consideration of building codes early in the design can avoid subsequent trouble. Often, problems can be prevented by no more than finding the right word to describe the purpose of the structure.

4. TWO EXAMPLES

4.1 CORRUGATED CULVERT

4.1.1. Design Description

The corrugated metal shelter concept (Fig. 4.1) is intended to provide high overpressure protection at the lowest possible cost for critical workers and homeowners in risk areas. The concept in the illustration is a modular design which can be expanded as far as the real estate will permit. In the accompanying illustration, entrances are shown repeated every 28 ft of shelter length for every 18 people. This ratio of population to entrances is typical of that which would be required for a population which was going to take shelter with only tactical warning, perhaps 15 minutes. Where longer warning times are available, fewer entrances could be used. A module 21 ft long containing space for 12 bunks would be recommended for a family.

This system is a variant of the concept pioneered by the Donn Corporation, which tested a 6-1/2-ft-diameter, .065-in. wall, 1 x 3-inch corrugated metal shelter in the MISER'S BLUFF event in 1978 (Donn, 1979). It was shown that this concept in the sizes tested would survive incident overpressures up to 150 psi from a 120-ton chemical explosive. The Donn configuration was ideal from the standpoint of promoting earth arching, but the long, horizontal entryways at each end and the 6-1/2-ft-diameter result in a shelter that is difficult to enter and awkward to use.

In this concept, the diameter is expanded to 9 ft, or 108 in. (2.7 meters), providing much more comfortable bunk arrangement; and, according to European experience, a much less oppressive psychological environment. Wall thickness is correspondingly increased to 0.108 in. to maintain the resistance to buckling.

The entrances are moved from the end to the side, and the entranceway shortened to 3 ft. The entranceways are made from two sections of 30-in.-ID, corrugated culvert. The vertical section extends 2 ft below the horizontal 3-ft section, which facilitates ease of entry and provides a little additional radiation protection. In the concept sketch, a 55-gallon drum is illustrated in the

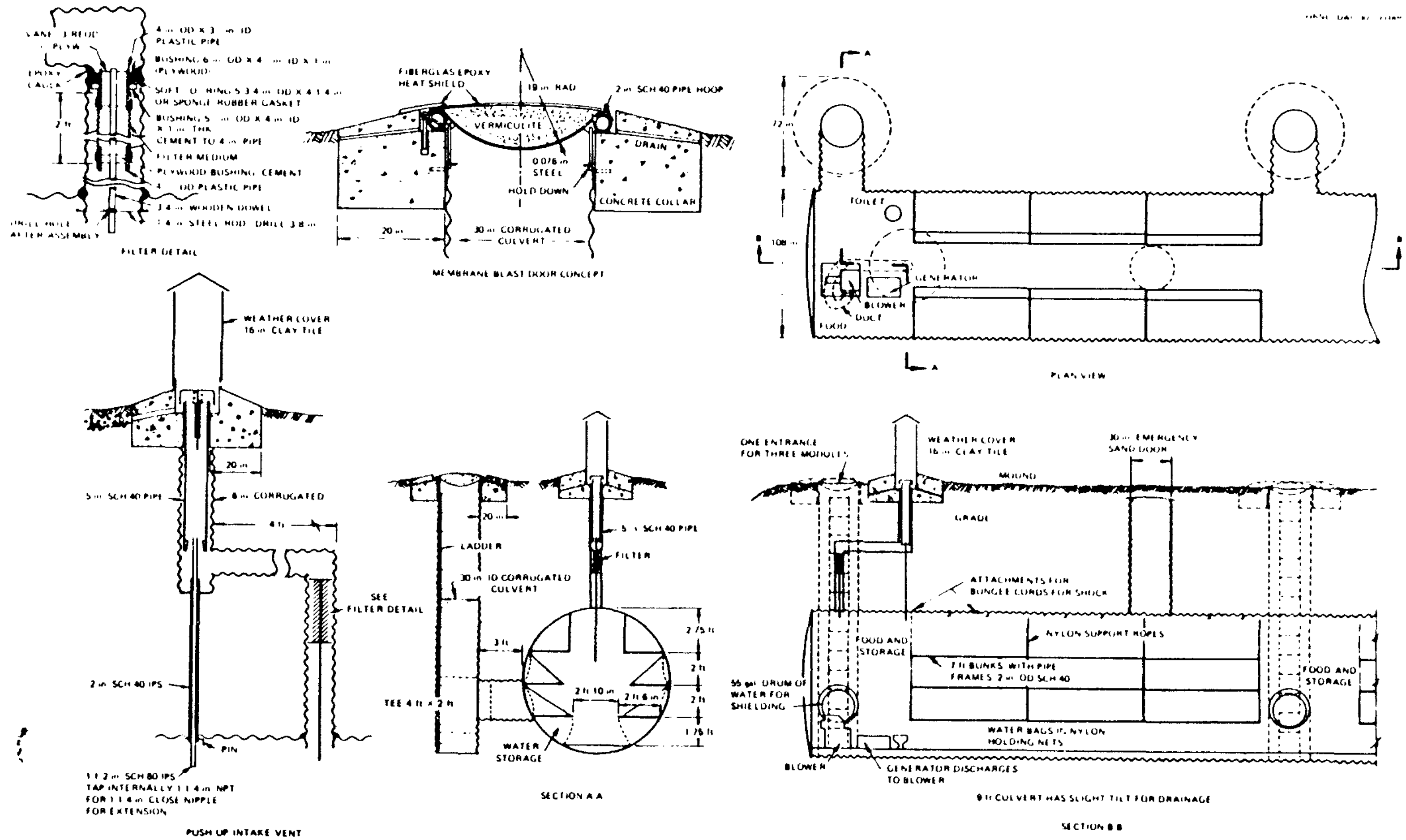


Fig. 4.1 Corrugated Culvert Shelter Concept

horizontal entranceway to provide some additional shielding against initial nuclear radiation. The drum is filled with water, which can be consumed during the shelter stay following the attack. The drum can be replaced by smaller water containers.

Neither this diameter of shelter in this gauge nor this entranceway configuration have been subjected to overpressure testing. Such tests must be conducted before any large-scale deployment of this shelter, in order to assure that earth arching will protect this configuration of entrance. At present, it is not possible to do a rigorous analysis of the three-dimensional stress distribution around the entranceway resulting from earth arching.

Habitability items such as toilet, blower, and a small generator are indicated in one end of the shelter, not necessarily in their optimum positions, but rather by way of reminder to cost estimators.

In the concept sketch, offset, push-up ventilation intakes are indicated, as is a sand-filled emergency escape hatch. This provision would be required on a one-entrance family module, but might not be necessary on a multientrance, industrial configuration.

4.1.2 Membrane Blast Door Concept

Doors and entranceways have long been recognized as a major cost component of shelters. They are a large contributing factor to the high cost per space of small shelters. Entranceways must exclude the blast pressure, attenuate external radiation (especially initial nuclear radiation) to an acceptable degree, tolerate the thermal environment produced by the weapon, and transmit the load on the door ultimately to the surrounding earth. Costs are minimized if the doorway configuration does not result in overpressure amplification in re-entrant corners, as can occur with exposed vertical doors or vertical walls. In general, the smaller the door, the more economical it will be.

The most economical door will be a horizontal hatch-type door on a vertical circular entryway, mounted flush with the ground. This will produce the smallest practical area, eliminate pressure amplification, and minimize debris problems.

The door concept illustrated in Fig. 4.1 uses a steel membrane of spherical shape as the pressure-supporting element. The membrane experiences no bending moments and, in contrast to arches or domes, is immune to buckling. It is the most efficient use of the strength of steel. For a given overpressure, the stress developed in the membrane is inversely proportional to its radius of curvature. Because the minimum radius of curvature equals the radius of the entranceway, for practical reasons it is usually more economical to design for a slightly larger radius. In the example shown, a door designed to resist 200 psi shock overpressure (equivalent to 400 psi static load) with a 19-in. radius requires a thickness of .076 in. of steel with a yield stress of 50,000 psi.

The edges of the membrane must be supported. For the design overpressure, it is believed that the most economical solution is an edge beam consisting of a circular hoop of 2 in., Schedule-80 steel pipe. The membrane, which can be pressed or spun, is formed with a lip which turns over the hoop and is welded. An angle of wrap around the hoop of approximately 120° decreases the stress on the weld under load.

The stresses on the hoop are complex. It is in longitudinal compression due to the radial component of the membrane force. The stress of the membrane tangential to the cross section of the hoop subjects it to an inward twisting force, which is resisted by a combination of compressive fiber stress in the upper half of the hoop and tensile fiber stress in the lower half, and the corresponding shear which these forces develop. The vertical component of the membrane working against the pressure of the seat of the door on its concrete collar tends to collapse the hoop by vertical crushing. This last force, which cannot be resisted by Schedule-80 pipe, is most economically provided for by pumping the pipe full of a high-compressive-strength grout.

In this concept, the concave volume of the membrane is filled with a high-compressive-strength, temperature-resistant material such as vermiculite, to protect the steel against the thermal pulse, avoid pressure amplification, and minimize drag on the door from horizontal blast winds. To protect the steel hoop against thermal pulse, and the vermiculite

against aerodynamic forces, it is suggested that the entire assembly be covered with a fiberglass-epoxy ablator.

One of the disadvantages of corrugated metal construction, as opposed to reinforced concrete construction, is that the structure of the shelter or the entranceway is not strong enough to support the load generated by doors and blast valves. Some stronger structure is needed to transmit these loads to the soil. In the case of this door, it is a concrete collar poured around the corrugated pipe with a smooth inside vertical surface that can slide down over the pipe. In this way, the load on the door will be transmitted to the soil without any longitudinal compressive stress in the vertical entrance pipe. The radial compressive stresses on the pipe developed by the soil are designed to be supported by the pipe.

The door is set in a recess to provide aerodynamic fairing and eliminate horizontal loads on the door from the blast winds. The recess must be drained to minimize the percolation of rainwater down along the entrance pipe, with its possible contamination.

The collar must be wide enough to resist being punched excessively far into the ground by the unsupported load of the door. It must be massive enough to hold down the door against the negative phase of the blast pressure, which can approacn 3 psi.

In the concept shown, a simple hinge is constructed of eye-bolts welded into the door edge and sitting in a hole in the collar. The door is to be fitted with hold-downs of unspecified design on at least 2 points around its perimeter.

The door will weigh approximately 100 lbs and should be fitted with either a counterweight or a spring compensator (which is not shown).

Development of this concept has not progressed far enough to permit accurate estimates of cost. It contains approximately 70 lbs of steel, can be fabricated by simple operations, and is amenable to mass production. In large numbers, the price may approach $200.

4.1.3 Ventilation Intakes

The design of low-cost ventilation intakes for a shelter which can survive up to 200 psi and cope with rain in a contaminated environment

and the 2000 mph wind accompanying a 200 psi shock presents a difficult design problem. High-cost solutions to these problems exist in the command bunkers of many countries in the western world, as well as the Soviet Union. In this study, two possible low-cost approaches to the problem are presented. In one, the push-up concept is explored. The winds and dynamic forces are avoided by simply having the intake pipe retracted to ground level and an expendable weather cover for the intake aboveground. After the blast, the intake pipe can be pushed up approximately 3 ft to provide rain protection and escape from any loose debris covering the intake.

In the other approach, the shelter is covered with a berm and a horizontal corrugated culvert is buried across the berm with openings on both sides. A third length of pipe is teed into the horizontal pipe and connects with the shelter.

4.1.3.1 Push-Up Intake Vent

A conceptual sketch of the push-up intake vent is shown in Fig. 4.1. The intake line, which is 6-in. corrugated culvert, has a 4-ft length connecting to the surface, a horizontal 4-ft segment about 4 ft below the surface connecting to another vertical 4-ft segment, which connects to the shelter. The piece connecting to the surface is surrounded by a concrete collar at the surface, which provides aerodynamic protection for the surface-mounted blast valve and transmits the load on the valve to the soil rather than the corrugated culvert. The valve is simply a pipe cap, or dome, over the end of the intake pipe and is held in the open position by a spring. It is difficult to design this type of closure to survive more than 50 psi.

The blast valve is mounted in a 3- or 4-ft-long piece of 5-in., Schedule-40 pipe, which can be pushed vertically upward after an explosion by means of a 1-1/2-in., Schedule-80 pipe attached to vanes in the bottom of the 5-in. pipe and extending down through another piece of pipe into the shelter. An extension of the 1-1/2-in. pipe would be screwed onto it when the 5-in. pipe was to be raised by an automobile jack.

The offset in the line provides radiation shielding. It is principally intended to provide a trap and a settling area for radioactive dust.

4.1.3.2 Horizontal Ventilation Intake

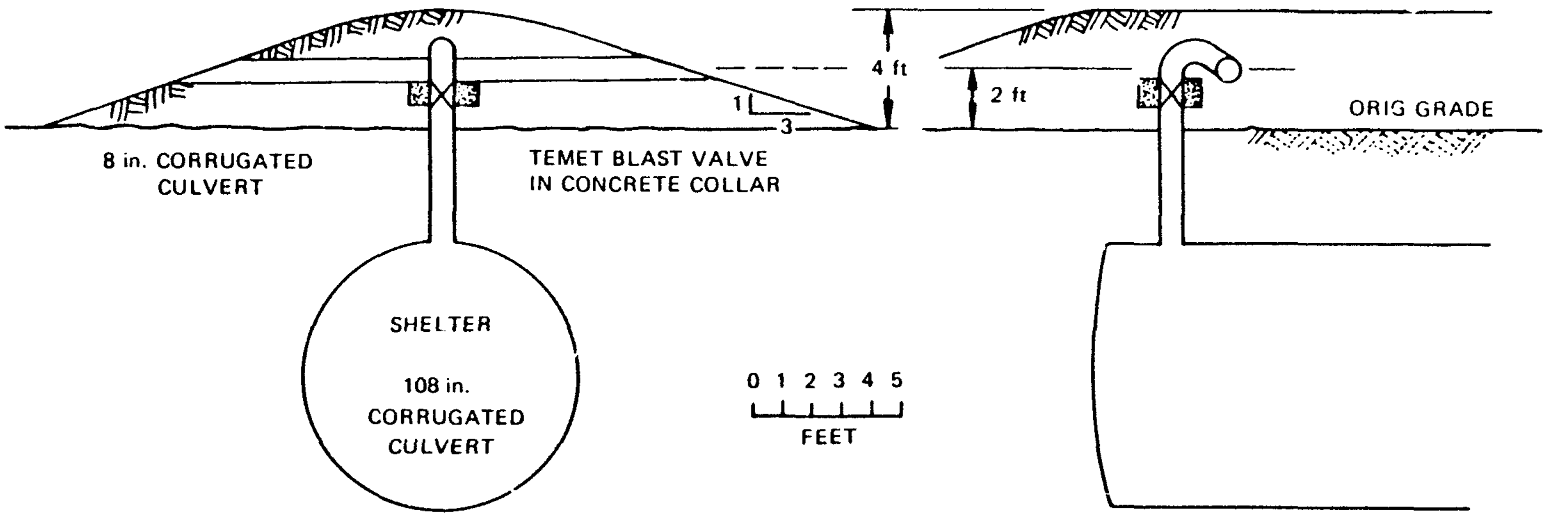
If the shelter is installed in an area that would permit construction of a berm over it, a horizontal ventilation intake may be installed (Fig. 4.2). This is a 6- to 8-in., corrugated culvert buried at a depth of about 2 ft in the berm, positioned transversely in the berm with the two ends of the pipe exiting the berm at a height approximately 2 ft above the original grade. Connection between the horizontal pipe and the shelter is made by an additional length of 6- to 8-in., corrugated pipe coming vertically up out of the shelter into a bend, which connects to the horizontal pipe on its upper surface. The purpose of the bend is to prevent rainwater from trickling down the intake pipe to the shelter and keep some of the larger dust particles out.

In this concept, a Temet© cylindrical-type blast valve is installed at the top of the vertical section of pipe coming out of the shelter. A concrete collar is cast around the blast valve to transmit the load on the valve to the surrounding soil, rather than to the corrugated pipe. Access to the blast valve must be obtained by digging down through the two feet of earth covering the assembly.

4.1.3.3 Dust Filter

A concept for a dust filter that can be installed in the intake line is shown in Fig. 4.1. It is intended that most of the dust be settled by gravity in the pipe upstream. The filter is intended to be a low-pressure drop, replaceable, air-conditioner filter medium rolled into a cylinder approximately 2 ft long. The filter cartridge can be inserted in the pipe from inside the shelter and replaced from i side the shelter. The clogged filter cartridges could be discarded temporarilyin the bottom of the entrance shaft. Placing the filter up inside the intake pipe so that its bottom is 18 in. from the shelter provides a geometric protection factor of approximately 60 immediately adjacent to the intake pipe in the

ORNL–DWG 82-19347



HORIZONTAL ENTRANCE VENTILATION INTAKE CONCEPT

shelter. Two feet away from the intake in the shelter, the radiation intensity at the filter is reduced by a factor of 1000.

4.1.4 Extending Life of Corrugated Metal

One of the concerns about corrugated steel is its potential for rusting, which is probably responsible for some hesitation in its adoption by shelter designers. However, as demonstrated by widespread application of corrugated culvert, galvanizing the steel permits service life in the ground for decades. In fabricated structures, great care must be taken that any welding is recoated with galvanizing or zinc-bearing paint. For exceptionally corrosive soil environments, an additional bituminous coating on the outside has been used at modest increase in cost.

We believe that the use of a small commercial dehumidifier in the interior of the space will help eliminate condensation on the walls and will further prevent corrosion from this direction. Painting may also be helpful.

For a long life in corrosive soils, cathodic protection can be employed. This can consist of connecting a large block of a more active metal such as magnesium to the outside of the structure buried in the soil. The magnesium is a sacrificial electrode which corrodes preferentially to the zinc and steel. A very long-lived system can be obtained by burying wires in the soil near the structure and applying a few volts of DC potential, charging the structure negatively with respect to the wires. In this way, service lives greatly in excess of 50 years can be easily attained even in wet soil.

4.1.5 Going to Higher Overpressures

There is no increase in the cost of buried portions of structures relying on earth arching when designing them for higher overpressures. However, at higher overpressures, there is some increase in the cost of the blast door and its support and blast valves and their supports, but these usually amount to only a minor portion of the cost of the structure.

Ground motion begins to become a problem at about 50 psi, especially in alluvial soils. Displacements of several inches can be observed from megaton-range weapons above 50 psi. Acceleration above 60 times gravity can be observed, but this is usually associated with the higher frequency, lower amplitude components of the shock spectrum. Simple and inexpensive methods can be used to protect able-bodied workers who have good tactical warning of an attack that would permit them to get in a less vulnerable posture. For example, a sling seat suspended from an overhead attachment by a bungee cord can provide protection against motion exceeding a foot in amplitude.

The most difficult design problem is coping with initial nuclear radiation at very high overpressures. For intermediate range weapons, doses in excess of 5 million rads can be experienced at 200 psi. Very large protection factors are required. The problem is compounded by the fact that this radiation is extremely penetrating. Fast neutrons and the very energetic nitrogen-capture gammas have attenuation lengths in soil which are much greater than that of fallout radiation.

The protection factor for the design proposed has been estimated by extrapolation of tests of a very similar geometry conducted at ORNL in 1964 at the Tower Shielding Facility (Cain, 1964). Measurements were made on a cylndrical, vertical entrance 4 ft in diameter, 12 ft deep. A horizontal tunnel 20 ft long was connected to the vertical shaft at the bottom. Three such structures were illuminated with neutron and gamma radiation approximating that from a fission weapon. The source was the tower shielding reactor, which was positioned at several angles of elevation.

It is estimated that for radiation from low (15°) angles of elevation, as from a groundburst, the entranceway suggested for the corrugated metal shelter has a protection factor of 2×10^5 for gamma rays and approximately 10^6 for neutrons. This is to a point five feet from the entrance inside the shelter, with a water drum or water bottles in the horizontal entrance.

The occupants of the shelter would receive a total dose of less than 25R from a one-megaton weapons groundburst 2300 ft away, which would also subject the shelter to 200 psi.

4.1.6 Corrugated Steel Culvert Shelter: Structure and Costs

Previous arguments have been introduced concerning the use of this shelter configuration for a wide variety of applications. The phenomenon of earth-arching is probably the major consideration in the applicability of this shelter to high blast regions. Because of this behavior, much thinner-walled culvert (with resultant cost savings in steel) can be used than would be expected if the cylinder had to bear the entire blast load. End pieces may be conical, dished, or flat steel with angle-iron reinforcement. The use of corrugations in the cylinder is an effective method of increasing resistance to buckling.

Further, more compelling arguments for the feasibility of this type of shelter are found in the extensive blast testing reported for buried culverts in the weapon testing program (Beck 1969) and more recently by the Donn Corporation.

We have already included cost figures for corrugated steel culvert shelters based on the estimates of Donn Corporation (1978) and the RTI study (Kamath and Wright [RTI] 1980). We believe that the more realistic estimate of the cost of such a shelter is given by the RTI estimate from their independent contractor, particularly if only a few shelters are constructed by a single contractor. However, we have updated the cost estimates for a corrugated steel culvert shelter, based on the design criteria shown in Fig. 4.1, with improved blast door and ventilation shafts and air filter. The discussion of the costs of the corrugated steel culvert shelter consists of two parts, earthwork and the main shelter, including habitability items. The costs for the earthwork associated with construction of blast shelters varied over a relatively wide range in the various design studies reviewed in this report. An approximate range for earthwork, as a percent of total direct costs, is 10-25%.

To estimate the costs of earthwork for our corrugated culvert shelter, we followed the standard technique of estimating costs of labor and materials for the types of crews normally used for small-scale excavation and backfill. The cost guide was R. S. Means, Building Construction Cost Data, 1981. The crews which we believed could conduct the job were B-7, B-30, B-10O, B-10D, 1CLAB (1 common laborer) and B-9.

The method of estimating the costs of earthwork for an 18-space corrugated culvert shelter is shown in Table 4.1. The cost of $1500 for the earthwork is probably on the high side of a national average number. Over half of this cost is due to extensive backfill and tamping requirements (but necessary for earth arching).

A local contractor in Knoxville, Tennessee estimated that the earthwork for the 27-ft-long, 18-man culvert could be completed for about $1000. The savings represented in this figure probably occurred because of two considerations: (1) the reduction in cost due to hard economic times for contractors; and (2) the savings possible with small companies that have low overhead costs.

The estimated cost of the earthwork was used with information about LOK-COR corrugated galvanized steel culvert manufactured by Republic Steel to estimate the cost for the total 18-space culvert shelter. The cost of the LOK-COR pipe varies with several factors, such as internal diameter, type of corrugation (depth and pitch), gage thickness, and type of coating. Options in coating include plain galvanized, galvanized and fully asphalt coated, galvanized and fully asphalt coated and paved. The purpose of asphalt coating is to extend the life of the culvert and consists of depositing a layer of bituminous material about 0.05 in. thick onto the galvanized surface. Variation of costs with some of these factors is shown in Table 4.2. Present considerations of loading for 8-ft burial and 100-200 psi overpressure suggest that a wall thickness of 0.108 in. (12-gage) will be sufficient for the culvert.

Cost estimates for the 18-space corrugated culvert shelter are given in Table 4.3, for three types of culvert coatings. Following is relevant general information concerning shelter items:

4.1.6.1 108-in. Corrugated Culvert

This material is available from Republic Steel Corporation in 3-in. x 1-in. corrugation. Price/ft is roughly equivalent to the cost for sectional plate, plus labor. For prices/ft as a function of gage, diameter, and coating, see Table 4.2.

Table 4.1 Resource Requirement for Earthwork for Corrugated Steel Culvert Shelter for 18 Persons
Materials and Labor, 1981 R. S. Mears

Activity	Unit	Crew Type	Output Units/Day	Matl/ Eqpt. Cost $/Unit	Labor Cost $/Unit	Total Cost $/Unit	O&P Matl/ Eqpt. Cost $/Unit	O&P Labor Cost $/Unit	Total Cost incl. O&P $/Unit	Quantity Required Units	Time Required Crew Hrs	Matl/ Eqpt. Cost	Labor Cost $	Tot. Cost $	Tot. Cost Incl. O&P $
Site clearance	acre	B-7	0.7	808 E	898	1706	889	1287	2176	0.12	1.4	97	108	205	261
Grub and stump removal	acre	B-30	2.0	449 E	163	612	494	231	725	0.12	1.4	54	20	74	87
Excavation	cu.yd.	B-100	760	0.44	0.23	0.67	-	-	0.81	165	1.7	73	38	111	134
Backfill (Machine)	cu.yd.	B-100	510	1.00 E	0.34	1.34	-	-	1.59	112	1.8	112	38	150	178
Backfill (Hand)	cu.yd.	1CLAB	12.0	0	8.13	8.13	0	11.60	11.60	50	33	0	407	407	580
Tamping (Air)	cu.yd.	B-9	165.0	0.73 E	3.05	3.78	-	-	5.20	50	2.4	37	153	160	260
															1520

4.1.6.2 30-in. Vertical Entrance Shaft

This material is available from Republic Steel in 2-2/3-in. x 1/2-in. pattern. It probably can be obtained in 3-in. x 1-in. corrugations at comparable prices. Also, 2-ft x 4-ft, 30-in. tees in 3-in. x 1-in. corrugations and appropriate tee attachment bands are available from Republic.

4.1.6.3 Concrete Collar and Dished Blast Door

The concrete collar requires some special form work and about 1.5 CY of concrete. The initial estimate for this work is $50 for formwork, $60 for concrete ($40/CY). The blast door is a unique problem. For single-family shelter at overpressures below 50 psi, the door can be constructed of laminated plywood (with appropriate heat shield), 5-in. to 6-in. thick, at a nominal cost ($20-$40).

To extend the use of this culvert shelter to high blast regimes (greater than 50 psi), it is desirable to have a dished door. We have made inquiries to several companies concerning fabrication of this dished door (dimensions as in Figure 4.1) in lots large enough to minimize the cost. Republic Steel estimated the cost at $80/unit, if 10,000 units were manufactured. This number was based on recovery of the $100,000 required to fabricate the pressing or spinning die.

Lukens Steel Co. of Rocky River, Ohio quoted a price of $271.00 for a 36-in.-diameter membrane blast cover in lots of 100 (Forsythe 1983). The cover would have a special lip to fit a 2-in. pipe hoop, a 19-in. radius of curvature, and thickness up to 3/16-in. In addition there would have a one time tooling charge of $15,000.

The final major item required for the dished door is the supporting hoop to be fabricated from 2.0-in., Schedule-80 steel pipe. The job includes bending the hoop to form the correct toroid, fitting the hoop with nipples for grout insertion, filling with grout, and fitting the hoop with attachments for hold-downs and the hinge. As a minimum, we estimate this total hoop job to require a pipe fitter and welder for 3 hours each, so that, for $25/hr, a cost of $150 is suggested. Thus the estimated cost for the blast door and collar is in the range of $300-$500, dependent on the use of plywood or a formed, dished door, with the

Table 4.2 Information on Republic Lok Cor Corrugated Culvert

MAIN BODY:

Culvert - 96" ID
(108" not available in 2-2/3" x 1/2")
(96" OD not available for thinner wall in this pattern)

Corrugations 2-2/3" x 1/2" Wall	0.168" (8-gage)	
Plain galvanized	$144.58/ft	
Fully asphalt-coated (not paved)	154.13/ft	
Fully asphalt-coated (paved)	164.75/ft	
Half asphalt-coated (paved)	161.32/ft	
3" x 1" Wall - 0.168" (8-gage)	**96" ID**	**108" ID**
Plain galvanized	$172.49/ft	$207.60/ft
Fully asphalt-coated (not paved)	183.01/ft	223.88/ft
Fully asphalt-coated (paved)	195.46/ft	239.09/ft
3" x 1" Wall - 0.109" (12-gage)		
Plain galvanized	$111.47/ft	$134.04/ft
Fully asphalt-coated (not paved)	124.51/ft	148.99/ft
Fully asphalt-coated (paved)	136.64/ft	163.83/ft
3" x 1" Wall - 0.064" (16-gage)		
Plain galvanized	$ 67.99/ft	$ 95.73/ft
Fully asphalt-coated (not paved)	80.71/ft	109.74/ft
Fully asphalt-coated (paved)	97.38/ft	123.88/ft

ENTRANCE:

30" ID Corrugated Culvert
(available only in 2-2/3"x1/2" pattern for 0.064",0.079",.109",0.138")

for 0.138" (10-gage)	
Plain galvanized	$ 35.87/ft
Fully asphalt-coated (not paved)	38.51/ft
Fully asphalt-coated (paved)	39.02/ft
for 0.064" (16-gage)	
Plain galvanized	$ 16.95/ft
Fully asphalt-coated (not paved)	19.29/ft
Fully asphalt-coated (paved)	21.32/ft

Table 4.3 Estimate of Resource Requirements for Corrugated Steel Culvert Shelter, 18-Person Capacity, Underground Burial (8-ft Earth Cover)

Activity Description	Costs Including O,P,C: Galvanized $134/ft	Costs Including O,P,C: Fully Asphalt-Coated (not paved) $142.99/ft	Costs Including O,P,C: Fully Asphalt-Coated (paved) $162.83/ft
MAIN SHELL, 3" X 1"	3618	4023	4423
Site Clearance	261	261	261
Grub and Stump Removal	87	87	87
Excavation	134	134	134
Backfill, machine	178	178	178
Backfill, hand	530	530	530
Air Tamping	260	260	260
Entranceway:			
Tee 3" x 1"	240	240	240
3 bands @ $50 ea.	150	150	150
17' of 30" culvert	388	388	388
Concrete collar and dished blast door	400	400	400
Sand door, 12' @ $22.73/ft 30"	273	273	273
2 ventilation shafts @ $200 ea clay pile, inside pipe, filter	400	400	400
2 end pieces	1400	1400	1400
Toilet	250	250	250
Blower	500	500	500
Electrical (generator and wiring)	500	500	500
Cots, 18 @ $15 ea., with supports and cords and Bungee cord suspensions	370	370	370
TOTALS	9989 (554/space)	10,394 (577/space)	10,794 (600/space)
Price recalculated for local area where local contractor quoted $1000 for total installation	9489 (527/space)	9894 (550/space)	10,294 (572/space)

stipulation that for the latter case to be economical, a large number of shelters would be required.

4.1.6.4 Ventilation Shafts

We have not decided yet which type of design to pursue for the ventilation system. The push-up type vent with spring-supported, pipe-cap, blast valve is shown in Figure 4.1 while the horizontal ventilation unit is shown in Figure 4.2. The latter vent would be fitted with a TEMET© or Luwa© blast valve (constituting most of the cost, in addition to basic pipe materials) and requires soil conditions where berms can be used. We have estimated the price of the vertical vent with push-up module at $200 each. The horizontal ventilation unit might be slightly more expensive.

4.1.6.5 End Pieces

Three types of design have been considered for this item - dished, flat plate with angle-iron support, and conical section. We contacted Lukens Steel, Knoxville Metal Culvert, and Republic Steel concerning end-piece fabrication. Republic Steel quoted $2000 for an end piece of 0.250-in. steel welded in place on the culvert. The design was a standard dished end used for closure of large underground steel tanks. Knoxville Metal Culvert estimated $700/unit for flat end pieces of 0.138-in. steel welded in place and galvanized. They also estimated $600-$700/unit if the end piece were fabricated as a conical section, allowing reduced wall thickness.

Lukens Steel Co. quoted a price of $425 for a 108-in.-diameter dished head in lots of 100 (Forsythe 1983). The head has a radius of curvature of 108 inches, is 3/16-in. thick, and weighs 538 lbs. In the same letter they quoted a price for a 108-in.-diameter, flanged, shallow dished head of $480 in the same lot size. The head has a 170-in. radius, 2 1/2-in. skirt flange, 0.130-in. thickness, and weighs 560 lbs.

4.1.6.6 Sanitation

We propose to use for the sanitary facility a Thetford marine toilet with hand pump ($250). The waste would be pumped through flexible tubing to a small cesspool outside the shelter. Percolation for only a gallon/day/occupant need be provided.

4.1.6.7 Air Blower

For a shelter housing 18 occupants, a blower capable of moving 400-800 ft^3/min (20-40 ft^3/min/occupant for hot weather) against 1.0 in. SP should be sufficient. We were quoted a price range of $400-$500 by New York Blowers for a unit capable of this work. For a blower capable of moving the 1500-2000 ft^3/min. required for a 54-space shelter, New York Blowers quoted a price of $835 for a 1.5-hp blower, 2-3-in. SP. However, this 2-phase, 240v motor could present generator interface problems. Cost of flexible duct work leading to exhaust vents is minor. The cost of moving ventilation air can be drastically reduced if Kearny air pumps are used.

4.1.6.8 Electrical

Homelite quoted $405 for a 1350-watt AC generator, 3600 rpm, 120 volts, single-phase, and $569 for a 2250-watt generator with similar operating specs. Wiring, outlets, etc., are relatively minor items.

Information on the costs for earthwork, structural items, and habitability items for the 18-space corrugated metal culvert shelter was used to estimate the costs of shelter housing 6, 54, and 108 occupants (Table 4.4). Independent estimates of structural items (no habitability items) for the 18-space culvert were obtained and are shown in Table 4.5 To show cost advantages of the corrugated metal over smooth steel or fiberglass tanks, we have included prices for comparable tanks in Table 4.6.

Table 4.4 Estimate for 6, 54, and 108 Spaces, Using Estimate for 18-Man Shelter

Activity	Cost: 18 Spaces	Cost: 108 Spaces	Cost: 54 Spaces	Cost: 6 Spaces
All earthwork, etc.	1500	9000	4500	500
Main shell, Fully asphalt-coated (paved)	4423	25538	13269	1474
Entranceway				
Tee 3" x 1"	240	1440	720	240
3 Bands @ $50 ea.	150	900	450	150
17' of 30" culvert	388	2328	1164	388
Concrete collar and blast door	200	120	600	200
Sand door	273	273	273	273
2 ventilation shafts/ clay pipe, blast valve ells/nubs/pipe/filter	400	800	400	400
2 end pieces, 0.250" thick, galvanized steel, welded in place	1400	1400	1400	1400
Toilet	250	500	250	250
Blower and flexible hose	500	1000	500	500
Electrical (generator & wiring)	500	1000	500	500
Cots with supports, Bungee cords	370	2220	1110	123
	10594	47599	25136	6398
	(589/space)	(441/space)	(465/space)	(1066/space)

Table 4.5 Estimate from Knoxville Metal Culvert for Metal Parts of Culvert Shelter (18-space)

Item	Cost/ Unit	Units	Total Cost
Bituminous Coated[a] 12-gage (0.108") 5 x 1 corrugations	150.26	27 ft	4057
End piece, 10-gage (0.138") flat steel, welded in place	700	2	1400
30" tee, 4' x 2', 14-gage	228	1	228
1' x 30" tee, fabricated from 108" galvanized steel	113	1	113
Ventilation shaft - 6", 16-gage (0.064"), BC corrugated steel pipe, with 1 stub, 1 tee, 1 ell, 20' of pipe	152	2	304
Entrance section - 30", 14-gage (0.079"), BC corrugated steel pipe with ladder, 10' of pipe	538	1	538
Emergency sand door w/fabrication	368	1	368
			7008

[a]Bituminous Coated - all metal galvanized

TABLE 4.6. COMPARISON OF FIBERGLASS, STEEL, AND CORRUGATED CULVERT TANK COSTS (COST/LINEAR FOOT)

TYPE	DIAMETER	LENGTH	SPACES	SPECIFICATIONS	COST
CORRUGATED CULVERT	8 FT	16 FT	6-10	12-GAGE, 0.109 IN.	$ 136.64
	8 FT	16 FT	6-10	8-GAGE, 0.168 IN.	195.46
	10 FT	34 FT	30	12-GAGE, 0.019 IN.	181.42
	10 FT	34 FT	30	8-GAGE, 0.168 IN.	265.31
STEEL	8 FT	16 FT	6-10	0.25-IN.	242.00
	10 FT	34 FT	30	0.3125 IN.	310.00
FIBERGLASS	8 FT	16 FT	6-10	NA	401.00
	10 FT	34 FT	30	NA	508.00

NOTE: CORRUGATED CULVERT IS FULLY ASPHALT-COATED AND PAVED. FOR GALVANIZED ONLY DEDUCT 20%. FOR FULLY ASPHALT-COATED ONLY, DEDUCT 10%.
STEEL TANK INCLUDES FIBERGLASS COATING ON EXTERIOR OF TANK, DIALECTRIC COUPLINGS AND 20-YR LIMITED WARRANTY.
STEEL COSTS FROM RBM COMPANY, KNOXVILLE, TN, 1982 FOB PLANTS. CORRUGATED CULVERT COSTS FROM REPUBLIC STEEL, KNOXVILLE, TN. 1982 FOB PLANTS.

4.2 A DUAL-USE RETROFIT WINE CELLAR

A preliminary study was made of a dual-use blast shelter to get an idea of what 1982 costs of a family shelter would be. The concept shown in Figs. 4.3 and 4.4 is furnished as a wine cellar in its peacetime configuration. In this configuration, it can also function as a playroom or a tornado shelter. It is shown fitted with combination cabinet-wine racks, which can be removed in a crisis to prepare the shelter for wartime function.

4.2.1 System Description

4.2.1.1 Structure

The shelter box is cast-in-place, reinforced concrete with standard reinforcement and 8-in.-thick floor, walls and roof. The exterior is covered with waterproofing and a 1-in.-thick layer of rigid foam insulation. The insulation serves the dual function of inhibiting condensation inside the shelter in warm weather and acting as a compressible backfill to promote earth arching. A design depth of cover equal to half the span will develop a great deal of earth arching if a reasonably granular soil is employed as backfill.

4.2.1.2 Ingress and Egress

Normal peacetime access to the shelter is through the basement of the house and a connecting vestibule. The vestibule is closed from the shelter and the house by standard exterior, industrial, hollow-core steel doors.

The vestibule is designed to be filled with sand as part of crisis preparations. The principle function of the sand is to arch over the slightly yielding steel door to the shelter and provide a high degree of blast protection. It also provides radiation shielding and, most importantly, protection from heat and carbon monoxide if the house should be set on fire.

At the end of the shelter farthest from the house, a vertical escape entryway is constructed. This consists of a 48-in. length of

ORNL-DWG 83-13445

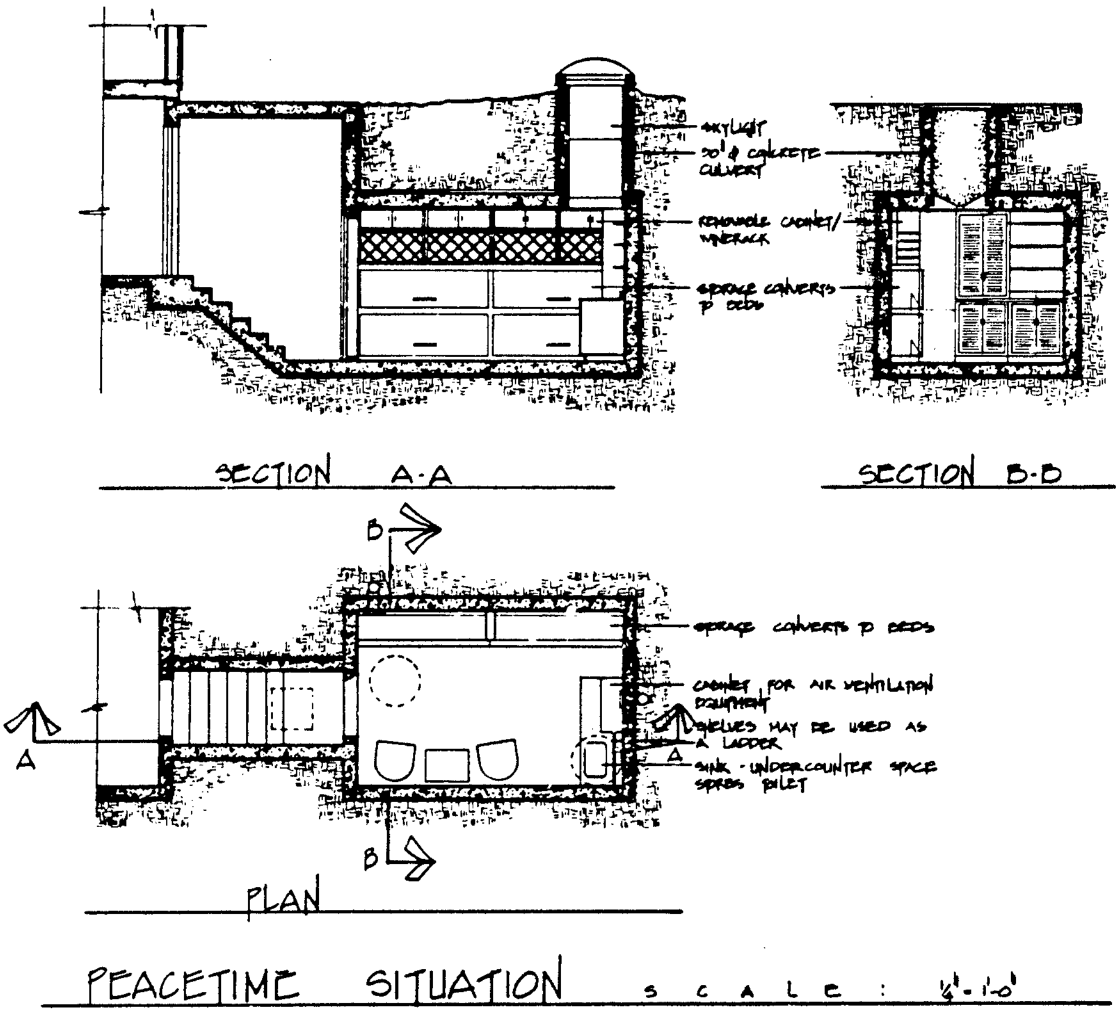


Fig. 4.3 Wine Cellar Shelter Peacetime Configuration

ORNL-DWG 83-13446

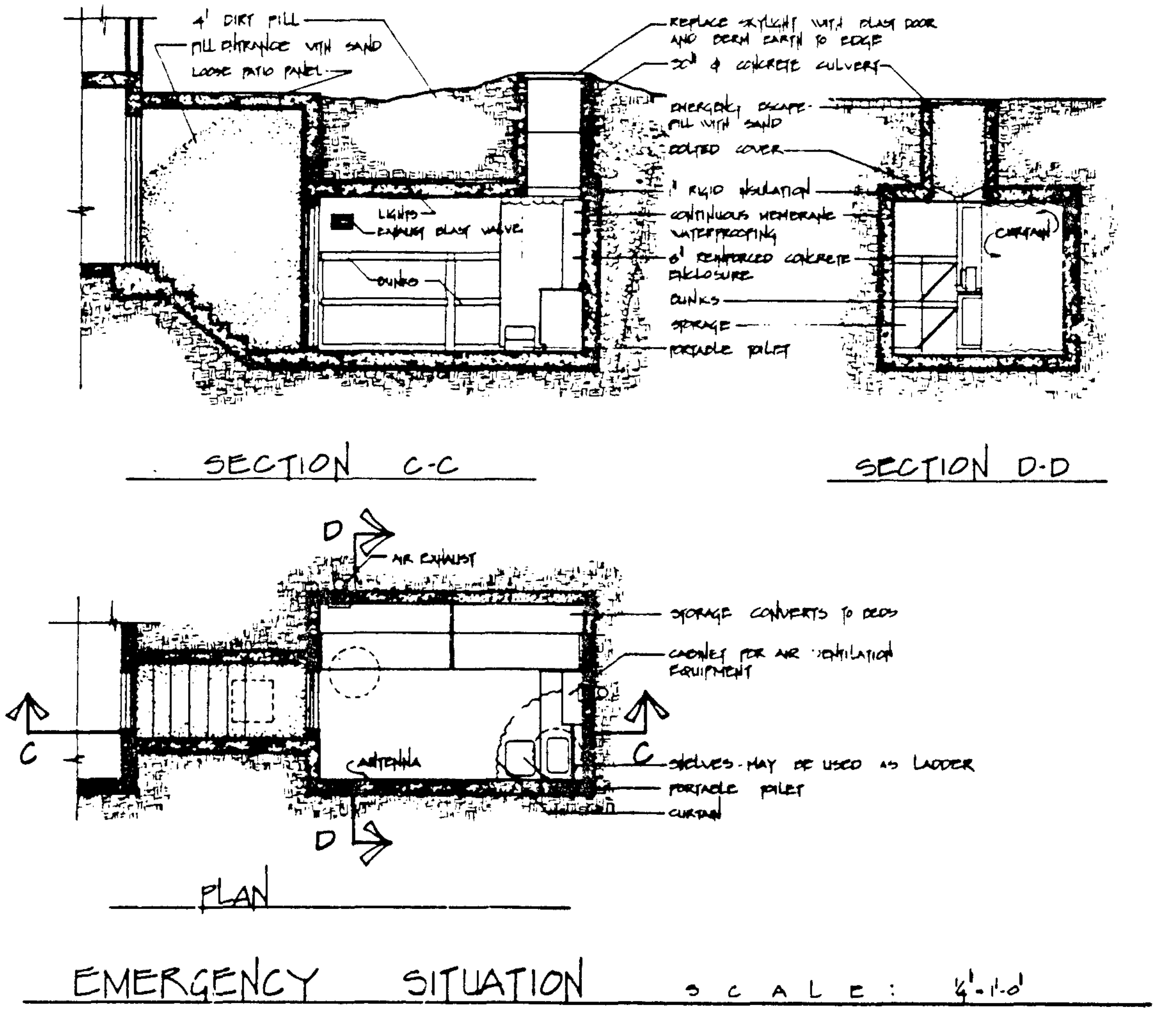


Fig. 4.4 Wine Cellar Shelter Crisis Configuration

30-in.-ID reinforced concrete pipe. Under peacetime conditions, it functions as a skylight and emergency escape tunnel; in wartime conditions, the skylight is removed and replaced by a 4-in. plywood blast door.

4.2.1.3 Ventilation

Peacetime ventilation is through the open doors and the ventilator in the skylight. Wartime ventilation is through two 4-in., Schedule-40 pipes connected to the walls of the shelter at opposite ends. A Luwa© air-handling system is specified, including blast valves, filter, and a hand-cranked blower, capable of delivering 200 ft^2/min.

4.2.1.4 Sanitation

Sanitation facilities specified are the equivalent of a Thetford recreational vehicle toilet, diaphragm pump, and a flexible pipe to an exterior cesspool several feet from the shelter. The cesspool would be underlain with enough crushed rock to permit percolation of the approximately 1 gal/day/occupant of waste that would have to be handled.

4.2.1.5 Occupancy

This shelter meets minimum floor space and volume standards for ten people. It is designed to be occupied by six people in relative comfort.

4.2.2 Protection Level

With the sand door in place and a backfill with a reasonable coefficient of internal friction, the shelter structure is extremely hard -- probably several hundred psi. The limiting vulnerability is the blast door. A door capable of supporting 50 psi is suggested, since above this overpressure, initial nuclear radiation and ground motion become troublesome.

More than 2-1/2 ft from the vertical entryway, the shelter has a protection factor for fallout radiation of 1000. Essentially all of the radiation enters the shelter through the vertical entryway.

4.2.3 Cost

Table 4.7 indicates the estimated cost of the shelter, both when constructed as part of the original house construction and also as a retrofit addition to a previously-existing house. It can be seen that the retrofit is about 12% more expensive than the shelter constructed with the house. Cost of the addition is just under $12,000. For six-person occupancy, this works out to $2000/space.

However, the structure also has a peacetime function -- as a wine cellar, playroom, or tornado shelter. The cost of the shelter which is attributable purely to its civil defense function is the ventilation equipment and the portable toilet, with a combined cost of approximately $1100. The incremental cost for equipment is only $200/space.

To be a fully functioning shelter, water and food must be stored. Water tankage typically costs on the order of $1/gal. Approximately 30 gallons should be stored for each prospective occupant, adding another $180 to the total cost of the shelter (or $30/occupant).

The belief is widely held that in the wake of a nuclear war, some considerable difficulty, delay and disorganization will be encountered in the reestablishment of food production and distribution. It would seem prudent to store several months' supply of emergency food for the shelter occupants. This can be as inexpensive as 12¢/day for something like corn meal.

This design concept needs considerably more refinement before it can be recommended for test construction.

Table 4.7 Cost of Wine Cellar Shelter

Division	As Part of New Construction	Addition to Existing House
(1) Earthwork	$ 510	$ 985
(2) Superstructure	4,368	4,368
(3) Doors and Hardware	650	720
(4) Thermal and Moisture	828	910
(5) Ventilation	775	775
(6) Plumbing	145	310
Toilet, Pump and Cesspool	300	300
(7) Electrical	205	295
(8) Demolition		200
(9) Specialties	520	520
(10) Cabinetry		
Sub-Total	$8,301	$ 9,383
Contractor's Overhead & Profit (20%)	1,660	1,877
TOTAL COST	$9,961	$11,260

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The overall purpose of this study was to examine ways to reduce the cost of shelter for critical workers. Shelters for this purpose would be expected to have from 10 to 100 spaces and overpressure protection in the range of 340-1360 kPa (50-200) psi.

The civil defense literature on cost was reviewed, and the cost estimates of the best designs were corrected to 1982 dollars. For shelters of the size and hardness of interest, costs generally run higher than $1000/space. Costs/space usually decrease significantly with increasing shelter size, and increase with hardness. None of the concrete shelter designs reviewed have taken advantage of earth arching. Experiments by the Donn Metal Products Company with a corrugated culvert shelter in the Miser's Bluff test suggest that for granular soils, corrugated metal culvert may be the most economical shelter design.

Basement shelter space in new buildings can be constructed at low cost; however, the threat to survival of its occupants from fire in the buildings or rubble from the building's destruction cannot be managed by entrance and ventilation intakes close to the building. Escape tunnels and ventilation intakes extending out some distance from the building are required.

Most of the cost of shelter is in the structure of the shelter itself. Possibly, the most effective method of reducing this cost is to exploit the phenomenon of earth arching. This is the tendency for the earth to develop shear strength under compression and transfer loads from yielding portions of an underground structure to non-yielding portions or to the soil itself. The power of this approach has been demonstrated dramatically by experience with corrugated metal shelter in the nuclear weapons tests in the 1950s. Consistent with a simple theory of earth arching, shelter survival depended much more heavily on the depth of cover of the shelter as a function of its span and the angle of internal friction of the soil, than on the strength of the shelter. Ten-gauge (3.57 mm thickness) corrugated metal shelters, 2.13 m (7 ft) in

diameter, survived 1.689 kPa (245 psi) with 3/05 m (10 ft) of earth cover in reasonably good soil. A 7.62-m (25-ft)-diameter, steel arch shelter with 1.52 m (5 ft) of gravel cover survived 699 kPa (100 psi).

Experiments with shallow-buried, rectangular concrete structures at the Waterways Experiment Station demonstrated substantial strength enhancement with depths of cover as little as 1/5 span. Depth of sand cover equal to 1/2 span was required to transfer most of the load on it to the walls and the surrounding sand.

A conceptual design and a cost estimate of a corrugated metal shelter was carried through the concept stage for 1.36 mPa (200 psi). It is believed the configuration used will enable the occupants to survive both the ground motion and the initial nuclear radiation from megaton weapons at this overpressure. The design was developed in consultation with the local vendor of Republic Steel Corrugated Culvert. Using their prices, it is believed that this shelter can be constructed for around $500/space, including habitability equipment, when purchased in relatively small numbers.

A design concept for a very lightweight, high-overpressure door was developed. This door, using the membrane principle, offers the promise of being the lowest-cost entranceway when in mass production.

5.2 RECOMMENDATIONS

The corrugated metal shelter concept proposed in this study should have prototypes constructed and field-tested. At least one test, possibly of a reduced scale model, should be subjected to megaton-duration overpressure above 200 psi.

The entryway geometry proposed should be analyzed for its protection factor for a radiation spectrum from a thermonuclear weapon, and the results compared with experimental data from a fission source for similar geometry. A prototype of the membrane blast door concept should be constructed and tested.

The push-up ventilator concept should be further developed and a prototype constructed and field-tested.

REFERENCES

Allgood, J. R. Summary of Soil-Structure Interaction. NCEL-TR-771. Naval Civil Engineering Laboratory, Port Hueneme, CA 1972.

Ammann & Whitney, Engineering Study of Atomic Blast Resistant Design for Several Different Building Types, AD 625 752, Contract DA 49-129-ENG-317 Ammann and Whitney, March, 1960.

Ammann & Whitney Study of Shock Isolation Methods for Civil Defense Shelters, Office of Civil Defense Work Order No.-OCD-OS-62-159, November 1963.

Bascom, W. A., Proposed Home Shelter, for the National Academy of Sciences Advisory Committee on Civil Defense, December 1956.

Bechtel Corp., Final Study Report for Protective Blast Shelter System Analysis, Prepared for the Office of Civil Defense, Contract No. OCD-PD-66-10, April 1967.

Beck, C., ed., Nuclear Weapons Effects Tests of Blast Type Shelters, CEX-68.3, U.S. Atomic Energy Commission, Civil Effects Branch, June 1969.

Bernard. R. D. and C. Wilton, The Effects of Building Collapse on Basement Shelters in Tall Buildings, SSI-8130-8, Science Service Inc., January 1983.

Bigelow, C. D., The Potential of Mass Production for Reducing Costs in Shelter Construction - A Preliminary Survey, Prepared for the Office of Civil Defense, Contract No. OCD-PD-64-201, March 1965.

Brown, William M., The Design and Performance of "Optimum" Blast Shelter Programs, HI-361-RR/2, Hudson Institute, June 1964.

Cain, V. R., C. E. Clifford, L. B. Holland, Measurements of Radiation Intensities in Vertical Concrete-Lines Homes and an Adjoining Tunnel at the Power Shielding Facility, ORNL-3513, Oak Ridge National Laboratory, March 1964.

Curione, C., Summary of Cost Trends of Mass Production As Applied to 5-10 psi Shelters, Prepared for OCD by Stanford Research Institute, Contract No. OCD-PS-64-201, Work Unit 1156A, February 1967.

Dateline Nuclear Fallout Shelter, Mark Two with Access Chamber, p. 20, Vol. 1, No. 3 March 1981, Protect and Survive Monthly.

Donn, Incorporated, Donn Blast Shelter Test No. 1 - Misers Bluff Event II-I, Final Report, Donn, Inc., Engineering & Research Division, 1000 Crocker Road, Westlake, Ohio, March 1979.

REFERENCES (Cont'd)

Donn Incorporated, Donn Blast Shelters Test No. 2, Miser's Bluff Event II-II, Final Report, Donn Inc., Engineering and Research Division, 1000 Crocker Road, Westlake, Ohio, August 1978.

Donn Incorporated, Blast/Fall-Out Shelter, Revised Edition, Donn, Inc., 1000 Crocker Road, Westlake, Ohio, December 1978

Emergency Measures Organizations, Plans and Specifications for Family Blast Shelters (30 psi), Ottawa, Canada, 1962.

Funston, N. E., T. H. Woo, E. York, "Expedient Blast Shelters Employing Soil Arching," National Convention of American Society of Civil Engineers, Pittsburgh, Pennsylvania, April 1978.

Forrestal, M. J., Protection Against High Blast Overpressure and Ground Shock, MR-1188, MRD Division of General American Transportation Corp., February, 1963.

Getchell, J. V. and S. A. Kiger, Vulnerability of Shallow Buried Flat-Roof Structures - Report 2, Foam HEST 4, TR-SL-80-7, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, October 1980.

Getchell, J. V. (op. cit.) Report 3, Foam HEST 5, February 1981.

Getchell, J. V. (op. cit.) Report 4, Foam HEST 3 & 6, December 1981.

Goen, R. L., John W. Ryan, A. C. Kamradt, Sanford Baum, and Milan Rodonic. Parametric Study of Shelter Costs, SRI Project MY 4536, December 1966.

Haaland, C. M., Systems Analysis of U.S. Civil Defense via National Blast Shelter System, ORNL-TM-2457, Oak Ridge National Laboratory, March 1970.

Harrenstein, H. P. Local Civil Defense Systems, Engineering Research Laboratory, University of Arizona, Tucson, Arizona, June 1964.

Harrenstein, H. P. and R. H. Gunderson, "Yielding Membrane Concepts," Proceedings of the Symposium on Soil-Structure Interaction, University of Arizona, Engineering Research Laboratory, Tucson, Arizona, September 1964.

Harrenstein, H. P. et al., A Study of Counterforce Defense System Methodology Applied to Tucson Arizona and Environs, AD 603 216, Engineering Laboratory, University of Arizona, June 1964.

Harrenstein, H.P. et al., "A Risk-Oriented Solution for a Target Community," Protective Structures for Civilian Population, April, 1965.

REFERENCES (Cont'd)

Harrenstein, H. et al., Yielding Membrane Elements in Protective Construction, Final Report, Prepared for the Office of Civil Defense, Contract No. OCD-OS-64-187, May 1965.

Harrenstein, H. P. et al., Cost Studies in Protecting Construction Systems, Prepared for Institute for Defense Analysis, Subcontract 138-4, June 1965.

Havers, J. A., Structural Materials for Hardened Personnel Shelters, IITRI-M-254, IIT Research Institute, December 1963.

Havers, J. A. and Jerry J. Lukes, Structural Cost Studies for Hardened Shelters (500-man and 1000-man capacities), IITRI-M-6064(I), IIT Research Institute, January 1965.

Holmes and Narver, Engineering and Costs Considerations for Tunnel Grid Blast Shelter Concept, Los Angeles, California, January 1976.

IITRI, Deliberate Shelters, Prepared for the Office of Civil Defense, OCD Contract DAHC-68-c-0126, December 1971.

Journal of Civil Defense Staff Study, "Private Shelter: Option for the Wary," J. of Civil Defense, Vol. 13, No. 4, August 1980.

Kamath, R. V. and M. D. Wright, Feasibility and Cost Analysis of Surge-Period Shelter Program, Final Report, RTI/1798000-05F, Research Triangle Institute, June 1980.

Kiger, S. A. and J. V. Getchell, Vulnerability of Shallow Buried Flat-Roof Structures, Report 1. Foam HEST 1 and 2, TR-SL-80-7 U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, September 1980.

Kiger, S. A. et al. (op.cit.) Report 5, Foam HEST 7, February 1982.

Kearny, Cresson H., Nuclear War Survival Skills, ORNL-5037, Oak Ridge National Laboratory, September 1979.

Krupka, R. A., Shelter Configuration Factors, Guy B. Panero, Inc., New York, 1963.

REFERENCES (Cont'd)

Lawrence Livermore Laboratory, A Study of Design and Cost Data for Family and Small-Group Fallout Shelters, UCRL-6654, October 1961.

Longinow, A. and O. J. Stepanek, Civil Defense Options for Fallout and Blast Protection (Single Purpose), IITRI-J-6115, IIT Research Institute, March 1968.

Longinow, A. H. Kalinowski, C. A.Kot, and F. Salzberg, Vol. I., Civil Defense Shelter Options: Deliberate Shelters, J-6144-I, IIT Research Institute, December 1971.

Longinow, A. et al., Vol. II., Civil Defense Shelter Options: Deliberate Shelters, J-6144-II, IIT Research Institute, December 1971.

Luscher, Ulrich Behavior of Flexible Underground Cylinders, L-TR-65-99, Massachusetts Institute of Technology. September 1965.

Means, R. S. Building and Construction Cost Data, 1981, R. S. Means Co., Inc., Kingston, Mass.

New Forge Works (Great Britain), "Survival Module Construction," Protect and Survive Monthly, Vol. 1, No. 10, p. 16, October 1981.

Nielsen, J. R., "Canadian Fiberglass Blast Shelter Trials," Protect and Survive Monthly, Vol. 1, No. 4, p. 11, April 1981.

Office of Civil Defense, Washington, D.C. Protective Structures, Shelter Design Series, (a) G35-1, September 1962 (rev.); (b) G35-2, April 1963.

Office of Civil Defense, Washington, D. C., Protective Structures, Shelter Design Series, (a) S55-1, September 1962 (rev.); (b) S-55-2, September 1962 (rev.); and (c) S55-3, August 1963.

Office of Civil Defense, Washington, D. C., Protective Structures, Shelter Design Series, (a) C45-1, August 1962; (b) C45-2, June 1963; and (c) C45-3, March 1964.

Robbins, D. T. and D. L. Narver, Jr., Engineering Study for Tunnel Grid Blast Shelter Concept for a Portion of the City of Detroit, Michigan, ORNL-TM-12223, Oak Ridge National Laboratory, September 1965.

Sawyer, H. A., "Economy Blast Shelter -- Family Style, SURVIVE (now Journal of Civil Defense) July-August, p. 10, 1969.

Sibley, Bruce, "Project Simplex," Protect and Survive Monthly, Vol. 1, No.,10, p. 18, October 1981.

Shimizu, B. et al, Parametric Study of Small Personnel Blast Shelters, HN-207, Holmes and Narver, October 1969.

Stevenson, J. D. and John A. Havers, Entranceways and Exits for Blast-Resistant Fully-Buried Personnel Shelters, IITRI-M-60645(2), III Research Institute, May 1965.

Tansley, R. S. and J. V. Zaccor, Testing of Shelter Design and Industrial Hardening Concepts at the Mill Race Event, SSI-8115.4, Science Service, Inc., January 1982.

Ward, Mike, "Concrete Survival No. 7, Value for Money," Protect and Survive Monthly, Vol. 2, No. 3, p. 14, March 1982.

APPENDIX A. COST DATA ANALYSES

APPENDIX A. COST DATA ANALYSES

The following routine was applied to analysis of the cost data presented in this appendix. In general, the costs/space for all the shelters in a single study were plotted (at constant occupancy) as a function of overpressure so that the most economical shelters could be identified. Normally, cost estimates for three cases of shock isolation - level 1, level 3, and none (all with the same degree of design and outfitting) - were plotted to present the maximum amount of information. Once the most economical shelters were identified, the costs/space for these shelters were plotted as a function of occupancy, for constant pressure.

Generally, those shelters which are most economical for cost/space are also most economical for costs expressed as cost/ft^2. However, there are some minor disagreements with conclusions in the original studies, but these variances are small enough to be ignored in a study most interested in establishing general trends. Also, no attempt has been made to reconcile the cost data for all studies so that the space allocated t each occupant in each unique shelter design was the same. This reconciliation was impossible in a number of studies because there was insufficient information concerning shelter dimensions and floor space.

In summary, although there may be slight disagreements in conclusions about costs/space, either with the initial document or later reviews, because of the use of costs/space as the major comparative cost parameter, we believe that it serves very adequately for the wide range of design conditions, shelter configurations, and design studies reviewed here.

Table A-1. Cost Information on Various Shelter Configurations from GATC Report (Forrestal 1963)

Over-pressure (psi)	Cost/ Person $ 1963	Unit Price for Shock Isolation Level 1	Unit Price for Shock Isolation Level 3	Unit Price for No Shock Isolation
GATC - Horizontal Steel Cylinder - 18-ft-OD, 2-story, 100 spaces				
100	263	2185	1818	1495
500	414	3072	2764	2354
1000	548	3832	3522	3114
1500	705	4723	4414	4004
GATC - Horizontal Steel Cylinder - 18-ft-OD, 2-story, 300 spaces				
100	154	1414	1037	877
500	282	2173	1854	1604
1000	408	2886	2568	2318
1500	534	3605	3287	3036
GATC - Horizontal Steel Cylinder - 28-ft-OD, 3-story, 300 spaces				
100	158	1591	1060	900
500	271	2260	1790	1541
1000	390	2936	2468	2218
1500	528	3718	3250	3000
GATC - Horizontal Steel Cylinder - 28-ft-OD, 3-story, 500 spaces				
100	137	1210	890	778
500	251	1882	1604	1427
1000	368	2545	2268	2090
1500	498	3287	3010	2832
GATC - Vertical Silo - 18-ft-OD, 100 spaces				
100	285	2309	1940	1618
500	442	3232	2923	2514
1000	611	4190	3882	3473
1500	776	5128	4818	4409
GATC - Sphere - 25-ft-diameter, 100 spaces				
100	303	2413	2046	1723
500	400	2990	2682	2273
1000	549	3836	3527	3118
1500	670	4528	4218	3809
GATC - Horizontal Concrete Cylinder - 18-ft-OD, 2-story, 100 spaces				
500	361	2768	2459	2050
GATC - Horizontal Concrete Cylinder - 18-ft-OD, 2-story, 300 spaces				
500	215	1790	1472	1223
GATC - Horizontal Concrete Cylinder - 28-ft-OD, 3-story, 300 spaces				
500	225	1846	1528	1277
GATC - Horizontal Concrete Cylinder - 28-ft-OD, 3-story, 500 spaces				
500	185	1504	1228	1050

Table A-2. Cost Information on Various Shelter Configurations from A&W

Over-pressure (psi)	Number of Spaces	Base Cost/ Space 1963$	Base Cost Shock Isolation 1963$	Cost/ Space 1982$	Cost/Space No Shock Isolation 1982$
- - - - - - - - - - - - A&W Shelters - - - - - - - - - - - -					
Rectangular cylinder, one-story, Protection Level 1					
25	250	186	78	1460	1118
25	100	225	114	1873	1373
25	10	367	166	3373	2645
Rectangular cylinder, one-story, Protection Level 3					
25	250	158	23	1066	965
25	100	181	38	1298	1132
25	10	348	35	265[illegible]	2504
Horizontal, concrete cylinder, two-story, Protection Level 1					
100	250	177	118	1614	1096
300	250	233	125	2014	1478
Horizontal, concrete cylinder, one-story, Protection Level 1					
100	250	257	115	2040	1535
300	250	306	130	2452	1882
Horizontal, concrete cylinder, one-story, Protection Level 3					
100	250	293	35	1886	1732
300	250	334	55	2276	2035
Horizontal, concrete cylinder, two-story, Protection Level 1					
100	100	225	152	2083	1417
300	100	301	158	2636	1943
Horizontal, concrete cylinder, one-story, Protection Level 1					
100	100	338	166	2764	2035
300	100	395	186	3272	2456
Horizontal, concrete cylinder, one-story, Protection Level 3					
100	100	374	71	2544	2232
300	100	432	90	3053	2[illegible]78
Arch, one-story, Protection Level 1					
100	250	434	104	2960	2504
100	100	553	166	3943	3215
Arch, one-story, Protection Level 3					
100	250	378	32	2338	
100	100	497	55	3149	

Table A-2 (continued)

Over-pressure (psi)	Number of Spaces	Base Cost/ Space 1963$	Base Cost Shock Isolation 1963$	Cost/ Space 1982$	Cost/Space No Shock Isolation 1982$
Vertical cylinder, two-story, Protection Level 1					
100	250	258	142	2162	
100	100	434	233	3583	
Vertical cylinder, two-story, Protection Level 1					
300	250	285	172	2521	
300	100	385	177	3618	
Horizontal, concrete cylinder, 2-story, Protection Level 3					
100	100	225	71	1728	
300	100	301	90	2340	
Horizontal, concrete cylinder, two-story, Protection Level 3					
100	250	177	35	1250	
300	250	233	55	1723	

Table A-3. Cost Information on Various Shelter Configurations from Havers Report (100-space shelters)

Over-pressure (psi)	Cost/ Space 1963$	1982 Unit Price for Shock Isolation Level 1	1982 Unit Price for Shock Isolation Level 3	1982 Unit Price for No Shock Isolation
One-Story Concrete Cylinder, 100 spaces				
10	150	588	588	588
50	155	610	610	610
50	155	1337	922	610
100	162	1364	947	636
150	174	1408	991	680
200	182	1442	1026	715
250	197	1588	1166	772
300	208	1632	1211	816
325	214	1654	1232	838
One-Story Steel Arch with Vertical End, 100 spaces				
10	130	509	509	509
50	142	552	553	553
50	142	1280	784	553
75	170	1391	904	662
100	202	1518	1031	789
One-Story Concrete Arch with Vertical End, 100 spaces				
10	107	416	416	417
50	122	478	478	478
50	122	1206	719	478
75	143	1290	803	561
100	170	1391	904	662
One-Story Concrete Cubicle, 7-ft bay				
10	90	350	350	351
50	120	474	474	474
50	120	1201	785	474
100	153	1325	908	596
150	174	1408	991	680
200	193	1574	1153	759
250	215	1662	1241	846
325	238	1750	1328	934
Two-Story Steel Cylinder, 100 spaces				
10	210	824	824	825
50	213	833	833	333
50	213	1500	1145	833
100	230	1566	1211	899
150	240	1606	1250	939
200	252	1654	1298	987
250	262	1720	1421	1026
300	275	1768	1469	1075

Table A-3 (continued)

Over-pressure (psi)	Cost/ Space 1963$	1982 Unit Price for Shock Isolation Level 1	1982 Unit Price for Shock Isolation Level 3	1982 Unit Price for No Shock Isolation
One-Story Steel Cylinder, 100 spaces				
10	178	697	697	697
50	185	724	724	724
50	185	1452	1036	724
100	204	1531	1114	803
150	221	1596	1180	868
200	228	1622	1206	895
250	242	1763	1342	947
300	255	1816	1394	1000
Two-Story Concrete Cylinder, 100 spaces				
10	162	636	636	636
50	168	658	658	658
50	168	1325	970	658
100	180	1373	1018	706
150	192	1417	1062	750
200	210	1492	1136	825
250	220	1553	1254	860
300	227	1583	1285	890
325	232	1606	1307	912

Table A-4. Cost Information on Various Shelter Configurations from Havers/Lukes (500-space shelters)

Over-pressure (psi)	Cost/ Space 1963$	1982 Unit Price for Shock Isolation Level 1	1982 Unit Price for Shock Isolation Level 3	1982 Unit Price for No Shock Isolation
Four-Story Concrete Sphere				
10	106	464	465	465
50	106	478	478	478
50	106	895	588	478
100	106	902	596	487
200	111	943	636	526
350	132	1070	803	632
Two-Story Steel Cylinder				
10	105	461	461	461
50	105	474	474	474
50	105	890	583	474
100	113	935	627	518
200	134	1036	728	618
Two-Story Concrete Cylinder				
10	73	334	333	333
50	76	355	355	355
50	76	772	465	355
100	78	794	487	377
200	85	846	539	430
350	103	960	693	522
One-Story Concrete Cylinder				
10	90	400	399	399
50	91	416	417	417
50	91	772	526	417
100	93	790	544	434
200	102	851	605	496
350	122	991	763	592
One-Story Concrete Arch				
10	61	289	289	289
50	71	342	342	342
50	71	662	439	342
100	102	794	570	474
125	143	956	732	636
One-Story Concrete Cubicle				
10	52	254	254	254
50	72	342	342	342
50	72	662	439	342
100	98	776	553	456
One-Story Steel Cubicle				
10	47	236	197	237
50	81	377	314	377
50	81	732	406	377
100	126	922	563	566

Table A-5. Cost Information on Various Shelter Configurations from Havers/Lukes (1000-space shelters)

Over-pressure (psi)	Cost/Space 1963$	1982 Unit Price for Shock Isolation Level 1	1982 Unit Price for Shock Isolation Level 3	1982 Unit Price for No Shock Isolation
Five-Story Concrete Sphere				
10	95	413	412	412
50	95	421	421	421
50	95	755	500	421
100	95	755	500	421
200	98	794	562	443
350	115	882	649	531
Two-Story Steel Cylinder, 20-ft diameter				
10	92	400	400	399
50	95	421	421	421
50	95	755	500	421
100	100	772	517	439
200	118	372	641	522
Two-Story Concrete Cylinder, 20-ft diameter				
10	67	302	303	303
50	67	312	312	311
50	67	644	390	311
100	69	654	400	320
200	78	719	487	368
350	90	785	553	434
One-Story Concrete Cylinder, 15-ft diameter				
10	88	386	386	386
50	90	400	400	399
50	90	649	491	399
100	92	662	491	412
200	99	732	570	452
350	114	808	644	526
One-Story Concrete Arch				
10	58	263	263	263
50	68	320	320	320
50	68	553	386	320
75	79	588	421	355
100	98	667	500	434

Table A-5 (continued)

Over-pressure (psi)	Cost/ Space 1963$	1982 Unit Price for Shock Isolation Level 1	1982 Unit Price for Shock Isolation Level 3	1982 Unit Price for No Shock Isolation
One-Story Structural Steel Cubicle				
10	45	215	215	215
50	78	355	355	355
50	78	588	421	355
100	117	741	575	509
One-Story Concrete Cubicle				
10	49	233	233	232
50	68	320	320	320
50	68	553	386	320
100	90	631	464	399

Table A-6. Typical Design Information from University of Arizona Study

	Percent of Total Shelter Cost							
	Individual Culvert	Flat-Plate Roof	Circular Dish Roof	Domed Roof	Concrete Box	Fixed Community Shelter System-4500	Rigid Type-1000 Concrete Cell	Multi-Purpose Buried Conduit
Excavation	5.2	9.6	8.5	10.4	9.5	7.5	5.1	23.0
Concrete	0.6	14.9	11.0	16.1	16.7	15.9	13.4	41.4
Reinforcing Steel or Conduit	0.3	19.4	13.3	12.6	15.0	23.1	16.7	
Timber							2.8	
Fabricated Structural Steel	47.6	16.3	31.9	17.4	12.6	5.2		
Corrugated Metal Pipe	13.4							
Miscellaneous on Entry						7.3	15.4	
Sealer Cost	1.5	2.1	1.8	2.1	2.5	0.5	0.6	
STRUCTURAL COSTS	69.0	62.2	66.5	58.9	56.3	59.5	54.0	64.4
Mechanical Ventilation Power Sanitary	21.2	25.9	22.9	28.1	29.3	19.4	23.0	15.3
Supplies Hotel Package Medical Package	9.7	11.9	10.6	12.9	14.4	21.0	23.0	17.6
Entrances								1.8
Operation Centers								0.9
TOTAL ESTIMATED COST, 1964$	11,816.23	9,658.45	10,901.26	8,891.26	6,138.45	1,427,119.00	280,338.26	124,167,392.00

Table A-7. Cost Information on Various Shelter Configurations from Krupka Report, No Habitability

Number of Spaces	Mid-1964 Unit Price, $	1982 Unit Price, $
Rectangular Reinforced Concrete, 100 psi		
5	346	1394
Rectangular Steel and Timber, 20 psi		
60	50	274
Rectangular Reinforced Concrete, 5 psi		
100	85	648
Reinforced Concrete Arch, 35 psi		
100	114	758
Reinforced Concrete Arch, 60 psi		
100	123	811
Reinforced Concrete, Horizontal Cylinder, 500 psi		
500	225	1028
Horizontal Steel Cylinder, 1500 psi		
500	670	2748
Rectangular, Reinforced Concrete, 5 psi		
1000	50	282
Rectangular, Reinforced Concrete, 35 psi		
1000	75	361
Rectangular, Reinforced Concrete, 60 psi		
1000	122	494
Reinforced Concrete, 2.5 psi		
5000	112	476
Reinforced Concrete, 30 psi		
5000	157	697

Table A-8. Cost Information on Various Shelter Configurations from Krupka Report, With Habitability

Number of Spaces	Mid-1964 Price, $	1982 Price, $
Corrugated Steel Arch, 10 psi		
100	156	692
Corrugated Steel Arch, 35 psi		
100	188	776
Corrugated Steel Arch, 10 psi		
100	54	547
Corrugated Steel Arch, 30 psi		
100	87	790
Reinforced Concrete, 30 psi		
2000	123	966
Reinforced Concrete, 3-4 psi		
2500	44	618
Reinforced Concrete, 17 psi		
3000	58	463
Steel Arch, 50 psi		
8000	238	1522
Steel Arch, 100 psi		
8000	281	1848

Table A-9. Cost Information for Various Shelter Configurations from Longinow & Stepanek Report

Over-pressure (psi)	Option 2 Cost/Space Mid-1957	Option 2 Adjusted to 1982	Option 3 Cost/Space Mid-1957	Option 3 Adjusted to 1982	Option 6 Cost/Space Mid-1967	Option 6 Adjusted to 1982
Rectangular, Reinforced Concrete, 500 spaces (austere package)						
10	143	477	187	603	225	750
20	147	490	185	617	229	763
30	163	543	201	670	245	817
Rectangular, Reinforced Concrete, 1000 spaces						
10	121	403	159	530	193	643
20	129	430	166	553	201	670
30	147	490	185	617	219	730
Rectangular, Reinforced Concrete, 5000 spaces						
10	117	390	155	517	183	610
20	127	423	165	550	193	643
30	145	483	183	610	211	703
Reinforced Concrete Arch, 500 spaces						
10	132	440	169	563	206	687
20	136	453	176	587	210	700
30	141	470	179	597	215	717
Reinforced Concrete Arch, 1000 spaces						
10	124	413	161	537	199	663
20	128	427	165	550	203	677
30	131	437	169	563	207	690
Reinforced Concrete Arch, 5000 spaces						
10	104	347	141	470	166	553
20	105	350	143	477	168	560
30	108	360	146	487	171	570
Steel Arch, 500 spaces						
10	128	427	166	553	203	677
20	143	477	181	603	217	723
30	167	557	205	683	241	803
Steel Arch, 1000 spaces						
10	123	410	161	537	199	663
20	138	460	175	583	213	710
30	158	527	195	650	233	777
Steel Arch, 5000 spaces						
10	106	353	144	480	169	563
20	120	400	157	523	182	607
30	140	467	178	593	203	677

[a]Option 2 - earthwork, basic structure, M&E, site preparation, etc., but M&E not 25% of basic, no extensive parking, 20% OP&C.

[b]Option 3 - loaded about the same as Option 6, with M&E about 25% of the basic, but no extensive parking, 20% OP&C.

[c]Option 6 - "Cadillac," with extensive parking provisions.

Table A-10. Cost/Space vs Pressure, from Holmes & Narver Study (Shimizu 1969)

Pressure	Cost/Space 1982 Level 1	Cost/Space 1982 Level 3	Cost/Space 1982 No SI	Cost/Space 1969
Fully Buried Concrete Rectangle, 20 spaces				
3	1598	1598	1598	300
25	2720	2720	2720	510
Fully Buried Concrete Rectangle, 50 spaces				
3	1384	1384	1384	260
25	1954	1954	1954	366
Fully Buried Concrete Rectangle, 100 spaces				
3	1306	1306	1306	245
25	1739	1739	1739	326
Fully Buried Concrete Rectangle, 200 spaces				
3	1228	1228	1228	230
25	1466	1466	1466	275
Fully Buried Concrete Arch, 20 spaces				
25	3064	3064	3064	575
60	4680	4254	3999	750
100	5608	5182	4926	925
Fully Buried Concrete Arch, 50 spaces				
25	1789	1789	1789	336
60	3048	2622	2366	444
100	3613	3187	2932	550
Fully Buried Concrete Arch, 100 spaces				
25	1483	1483	1483	278
60	2461	2083	1895	356
100	2752	2372	2185	410
Fully Buried Concrete Arch, 200 spaces				
25	1278	1278	1278	240
60	1994	1748	1640	308
100	2113	1868	1759	330

ORNL/5958
Dist/Category UC-41

INTERNAL DISTRIBUTION

1. Central Research Library
2. Document Reference Section
3-5. Laboratory Records Department
6. Laboratory Records, ORNL R.C.
7. ORNL Patent Office
8-27. Emergency Technology Library
28. B. G. Arrington
29. V. D. Baxter
30. S. A. Carnes
31. C. V. Chester
32. J. E. Christian
33. R. M. Davis
34. R. C. Durfee
35. W. Fulkerson
36. K. S. Gant
37. K. S. Gaddis
38. C. M. Haaland
39. D. Jared
40. S. I. Kaplan
41. S. V. Kaye
42. F. C. Kornegay
43. A. L Lotts
44. F. C. Maienschein
45. F. W. Manning
46. J. W. Michel
47. L. M. McCold
48. D. C. Parzyck
49. A. M. Perry
50. C. H. Petrich
51. B. E. Peterson
52. D. E. Reichle
53. C. R. Richmond
54. M. W. Rosenthal
55. T. H. Row
56. H. B. Shapira
57. D. B. Trauger
58. D. Torri-Safdi
59. T. J. Wilbanks
60. G. P. Zimmerman
61. G. C. Rizy
62 J. H. Sorensen
63. D. W. Holladay

EXTERNAL DISTRIBUTION LIST

64. AFWL/Civil Engineering Division, Kirtland Air Force Base, NM 87117

65. Air Force Weapons Laboratory, Attn: SUL Technical Library, Kirtland Air Force Base, Albuquerque, NM 87117

66. Applied Research and Associates, Attn: Cornelius J. Higgins, 2601 Wyoming Blvd., Suite H-1, Albuquerque, NM 87112

67. Assistant Secretary of the Army (R&D), Attn: Assistant for Research, Washington, DC 20306

68. James Beck Associates, 4216 Los Palos Avenue, Palo Alto, CA 94306

69. Donald A. Bettge, Office of Civil Preparedness, National Preparedness Federal Emergency Management Agency, Washington, DC 20472

70. Dr. William Chenault, Human Sciences Research, Inc., Westgate Industrial Park, 7710 Old Springhouse Road, McLean, VA 22101

71. Civil Engineering Center AF/PRECET, Wright Patterson Air Force Base, OH 45433

72. Dr. John Cockayne, Senior Scientist, Science Applications, Inc., 1710 Goodridge Drive, POB 303, McLean, VA 22101

73. Commanding Officer, U.S. Naval C.E. Laboratory, Attn: Document Library, Port Hueneme, CA 93401

74. George A. Cristy, 385 East Drive, Oak Ridge, TN 37830

75-87. Defense Technical Information Center, Cameron Station, Alexandria, VA 22314

88. Ray Derby, FEMA Special Facility, Box 129, Berryville, VA 22611

89. Dikewood Corporation, 1613 University Boulevard, NE, Albuquerque, NM 87102

90. Director, Defense Nuclear Agency, Attn: Technical Library, Washington, DC 20305

91. Director, Defense Nuclear Agency, Attn: Tom Kennedy, Washington, DC 20305

92. Director, Lovelace Foundation 5200 Gibson Boulevard, SE, Albuquerque, NM 87108

93. Director, U.S. Army Engineer, Waterways Experiment Station, POB 611, Attn: Document Library, Vickburg, MS 39180

94. Porter Driscoll, Research Coordinator, The Construction Sciences Research Foundation, Inc., 1150 Seventeenth St., NW, Washington, DC 20036

95. Dr. A. E. Fiorato, Construction Technology Laboratories, A Div. of the Portland Cement Assoc., 5420 Old Orchard Road., Skokie, IL 60077

96. GARD, Inc., 7449 N. Natchez Avenue, Niles, IL 60648

97. Dr. Ralph L. Garrett, 2 Catspaw Cape, Coronado, CA 92118

98. Manuel D. Herz, 106 Administration Road, Oak Ridge, TN 37830

99. Edward L. Hill, Research Triangle Institute, POB 12194, Research Triangle Park, NC 27709

100. W. L. Huff, USAE Waterways Experiment Station, POB 631, Vicksburg, MS 39180

101. Dr. Fritz R. Kalhammer, Director, Energy Management and Utilization Division, Electric Power Research Institute, 3412 Hillview Avenue Palo Alto, CA 94303

102. Kenneth Labs, Undercurrent Design Research, 147 Livingston Street, New Haven, Connecticut 06511

103. Dr. Todd R. LaPorte, Prof., Political Science, Institute of Government Studies, University of California, 109 Moses Hall, Berkeley, CA 94720

104. Richard Laurino, Center for Planning and Research, 2483 East Bayshore - Suite 104, Palo Alto, CA 94303

105. Jud Leech, BDM Corporation, 1801 Randolph Road, SE, Albuquerque, NM 87106

106. Anatole Longinow, College of Engineering, Valparaiso University, Valparaiso, IN 46383

107. Los Alamos Scientific Laboratory, Attn: Document Library, Los Alamos, NM 87544

108. Dr. Clarence R. Mehl, Division 1112, Sandia National Laboratories, Box 5800, Albuquerque, NM 87185

109. Joseph E. Minor, Texas Technological College, Lubbock, TX 79408

110. Ronald J. Morony, Building Tech. Div., Office of the Asst. Secretary for Policy Development and Research, Dept. of Housing and Urban Development Rm. 8162, Washington, DC 20410

111. Laurence I. Moss, Energy/Environmental Design and Policy Analysis, 5769 Longs Peak Route, Estes Park, CO 80517

112. Dr. Jiri Nehnevajsa, Social Science Department, University of Pittsburgh, Pittsburgh, PA 15260

113-114. Division of Energy Programs and Support, Oak Ridge Operations, U.S. Department of Energy, P. O. Box E, Oak Ridge, TN 37830.

115. Mike Pachuta, Federal Emergency Management Agency, Civil System Division, Washington, DC 20472

116. RAND Corporation, Attn: Document Library, 1700 Main Street, Santa Monica, CA 90401

117. John Rempel, Center for Planning and Research, 2483 E. Bayshore, Palo Alto, CA 94303.

118. Dr. Milton Russell, Director, Center for Energy Policy Research, Resources for the Future, 1755 Massachusetts Avenue, NW, Washington, DC 20036.

119. Leo A. Schmidt, Institute for Defense Analyses, Program Analysis Division, 400 Army-Navy Drive, Arlington, VA 22202

120. Phillip M. Smith, Associate Director, Natural Resources & Comm. Services, Office of Science and Technology Policy, Executive Office Bldg., Washington, DC 20500

121. Lewis V. Spencer, Room C303-Building 245, Washington, DC 20234

122. Walmer Strope, 5600 Columbia Pike, Suite 101, Bailey's Crossroads, VA 22041

123-143. Ralph Swisher, Federal Emergency Management Agency, National Preparedness Programs, Washington, DC 20472

144. Carl Taylor, Adams Craft Hertz and Walker, 106 Administration Road, Oak Ridge, TN 37830

145. Technical Information Center, U.S. Department of Energy, POB 62, Oak Ridge, TN 37380

146. Dr. William H. Williams, Div. Mgr., American Bell, Bldg. 83, Rm. 1B23, 100 Southgate Parkway, Morristown, NJ 07960

147. Thomas Watermann, IITRI, 10 West 35th Street, Chicago, IL 60616

148. Carl Wiehle, Defense Intelligency, Attn: CKW-DB-4C2, Washington, DC 20301

149. Prof. E. P. Wigner, 8 Ober Road, Princeton, NJ 08540

150-151. C. Wilton, Scientific Service, Inc., 517 East Bayshore Drive, Redwood City, CA 94060

152-153. Allan M. Ziebarth, President, Earth Shelter, Inc., 3528 Dodge Street, Suite 2B, Omaha, Nebraska 68131

154-379. Distribution Category UC-41.